INVESTIGATION OF DISTORTION
REMOVAL IN WELDED STRUCTURES

by

RICHARD A. WALSH XIII-A

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Chairman, Departmental Committee
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INVESTIGATION OF DISTORTION REMOVAL ON WELDED STRUCTURES

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ABSTRACT

The procedures for flame straightening of welded plates and structures are discussed and selections made for study in this thesis. System models were constructed of 1/2 in. mild steel and HY-80 steel plates to approximate plate and stiffener construction in ship fabrication. Flame heating temperature and point of application were varied in the experiments. Welding procedures, water quench rate and flame heating processes were maintained constant.

The results are given in the form of distortion plots, tables and photographs of post heating specimens. In this study it was shown that flame straightening of HY-80 steel structures and plates is less effective in reducing weld distortion, whereas, for mild steel the process is effective. Also, varying the point of heat application has varying effects on the amount of distortion removal.

This study represents a first step in the investigation of flame straightening techniques on welded structures. Recommendations for additional testing and analysis are given with particular emphasis in defining a corridor of materials with yield strengths appropriate for flame straightening application.

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Title: Associate Professor of Naval Architecture

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NOMENCLATURE

A_1	cross-section area of heat affected zone in fillet weld
A_2	cross-section area of surrounding base plate in fillet weld
d	deformation, inches X 10^{-3}
E	Young's Modulus, psi
I	welding current, amps
n	number of weld passes
$P_{1,2}$	load on three bar system model of fillet weld
P_o	oxygen pressure, psi
P_a	acetylene pressure, psi
s	station for deformation readings, inches
T	temperature, degrees fahrenheit
T_H	flame heating temperature, degrees fahrenheit
V	welding voltage, volts
α	thermal coefficient of expansion, per degree fahrenheit
ϵ	strain, in./in.
σ	thermal heating stress, psi
σ'	upsetting stress, psi

I. INTRODUCTION

A. Background of Problem

Control of distortion in large welded structures becomes a critical problem when the welded structure performs an important function. This is particularly true for shell plating in welded ships. Experiences concerning corrugation failures of bottom shell plating on large cargo vessels are known to exist. Initial corrugation of shell plate from fillet welding between shell plate and floor plate can contribute to corrugation failures under proper loading conditions[16]. Since welding of ships has become the most used method of fabrication, much has been written on weld distortion in shipbuilding[5,6,7,13,15,16,17]. Some of these articles are listed in the reference.

The basic phenomena of weld distortion caused by welding cycle stresses are:

(1) strains and plastic upsetting in the weld and weld area during the heating cycle.

(2) strains produced in the weld and surrounding area (heat-affected zone) during the cooling cycle.

Also, since it is improbable to have absolute rigidity in the surrounding plate near the weld, deformations are almost certain to occur[17]. For the structure

of shell plate and floor plate configuration this deformation takes the shape of an "arc-form"[5]. Excessive initial deformation of this type reduces the buckling strength of the bottom plating and hence makes corrugation failure more likely to occur.

The recognized first step to reduce this arc-form deformation is to minimize the distortion effects during the actual welding process. This is accomplished by proper sequence of welding, production planning, etc.[6,10] Malisius in his paper[15] lists numerous techniques to control transverse shrinkage, longitudinal shrinkage and angular distortion during weld processes. Although these fabrication procedures may reduce the initial amount of distortion they may not reduce them to acceptable tolerance levels. Once sections on the ship are on the ways proper welding sequence methods may not be possible. In this instance welding operations would produce distortion which would remain in the structure unless another method of distortion removal were used. To remove distortion incurred in the latter operation, shipbuilders use flame straightening procedures on low carbon steels.

There are two major problems associated with flame straightening procedures. The first concerns the change in mechanical properties in materials subjected to flame straightening techniques. The

second problem concerns which materials can effectively be subjected to these techniques and what type response do these materials exhibit as a result of the process. The former problem is presently being investigated at a commercial research center. The latter problem is the subject of this thesis.

The problem to be studied in this investigation is to compare flame straightening procedures as used on system models made of mild steel and HY-80 steel, and to observe distortion distributions of these systems in the as welded and post flame straightened condition. To prepare for this investigation a search of available literature was made to provide a firm background. Also, visits to local shipbuilding yards were made whereby the author could observe the process as it was performed on vessels during fabrication.

B. Previous Investigations

A search of the literature on flame straightening theory and shrinkage distortion produced limited results concerning previous experimental investigations or analyses. This was particularly true with respect to welded plates and structures. The application of flame straightening procedures in shipyards is more of an art performed by the worker than a production technique performed step by step.

Flame straightening theory relies on the same

phenomena as welding, that is expansion and contraction of the material[1,2]. Steel expands or contracts in definite ratio to each degree of temperature change. The application of heat to the material must force the material to expand into itself in lieu of normal expanding in length. This means that colder surrounding material must produce the inward force on the heated zone[2]. Mr. Holt[1] showed that three basic facts must be known concerning a material to be flame straightened. These facts are:

1. thermal expansion characteristics of material with a rise in temperature.

2. variation of yield strength of material with rise in temperature.

3. behavior of modulus of elasticity at elevated temperatures.

He further explains that when an area is heated and then cooled, the material contracts in volume and exerts a pull that is equal to the yield point at the temperature of the cooled volume. Maeda and Yada[8,11] performed analytic studies of single spot and multiple spot heating on homogeneous rectangular plates in simulation of flame heating procedures. Their solutions relate shrinkage in flame straightened plates as a function of the contraction or "dilation" force, Young's modulus for the plate and the breadth of the plate. The dilation force is a function of the yield strength

of the material and the breadth squared.

Previously, there has been no attempt to assess the effects of flame straightening techniques on higher yield strength materials. Since the flame temperature during the process is about 1200-1400 F one is aware that the critical temperature for quenched and tempered steels becomes important. Care must be taken not to exceed this temperature during heating and cooling cycles used in flame straightening. If the temperature is exceeded base properties of the material and the microconstituents will change. Rapid cooling (quenching) processes increase the maximum heating temperature for high strength, quench and tempered steels in flame straightening procedures without changing the metallurgical matrix of the material. Reference to standard time-temperature-transformation curves for each material will give acceptable rates.

C. Selection of Parameters

Mild steel and HY-80 steel were selected as the materials to be investigated. Mild steel is used extensively in ship construction for conventional tankers, cargo carriers, etc. HY-80 steel is used in the construction of submarines and research vessels for subsurface oceanographic explorations. Plate thickness of 1/2 in. was selected as standard for

all types of specimens used in this investigation. This thickness gives the greatest distortion characteristics for the size specimens used and the fabrication techniques employed in their construction.

Geometric configurations were selected based on the actual system to be studied, i.e. plate and stiffener joint construction as found on ship hulls. The first specimens of perpendicular plates PP-MS, 80-1, 2 represents the simplest model system for the fillet joint. The next series of perpendicular plates PP-MS, 80-3, 4 represents two fillet joints with plate span between them. Free-end and rigid-end structures were chosen to complete the progression for the system model. The reason for choosing the four varieties was to study the smallest system model consistent with laboratory facilities which would exhibit response characteristics of the actual system. The physical dimension of the specimens were dictated by laboratory facilities.

Flame heating temperatures were selected as 1200-1500 F for this investigation. This range coincides with procedures being used for research for the Ship Structures Committee under project SR-185. In studying material degradation care must be used in selecting heating temperatures for HY-80.

However, in this study deformations are being examined only, therefore, strict control of temperature is considered of secondary importance.

Oxygen and acetylene pressures during the flame heating operations were maintained constant at prescribed values for the cylinder, double regulator value rig used. A single nozzle number 30 tip oxy-acetylene torch was used for all flame straightening procedures.

D. Purpose of Study

Since there are no previous experimental investigations into flame straightening effects on welded structures, this study represents the first step in this area. The purpose of this study is:

1. to design and construct system models representing plate and stiffener joints found in ship construction.

2. to observe the response of these mild steel and HY-80 welded model systems to flame straightening procedures, and

3. to attempt an analysis of the results for extrapolation to other materials and other procedures.

II. PROCEDURES

A. Scope of the Research

A series of investigations were made of deformation changes resulting from flame straightening techniques on welded plates and structures made of mild steel and HY-80 steel. System models of plating and stiffeners were constructed to represent ship plate and frame construction found in shipbuilding fabrication. By studying these models insight into flame straightening application in ship construction was achieved. The point of heat application was varied for different specimens. Temperature range of the heating flame was varied between 1200-1500 degrees farenheit. Welding procedures were dictated by the equipment available in the M.I.T. Materials Joining Laboratory and the size and nature of the test specimens. These conditions necessitated using manual, covered electrode welding techniques.

B. Description of Specimens

For this study 1/2" thick plates were used for all specimens. It was believed this thickness would yield better distortion characteristics for the welding procedures used. By using this dimension heat input to the plates during the welding process would be less rapidly conducted away from the weld and heat affected

zone than in a thinner plate and the temperature gradient through the plate thickness would be greater than in a thinner plate.

Free-end and rigid-end refer to the boundary condition at the end of the vertical plates opposite the fillet weld. A standard H-beam 8"x8"x5' (35 lb./ft.) was used to establish the rigid-end boundary condition. The H-beam prevents the end opposite the fillet welds from moving independently of one another and prevents any angular changes of the fillet joints independently of one another. A single pass double fillet weld was considered adequate to establish the rigid boundary condition. Mild steel and HY-80 specimen plates were furnished by Boston Naval Shipyard. Cutting and finishing plates to specimen dimensions were performed in the machine shop of M.I.T. Metallurgy Department. The standard H-beam was procured locally through an iron and steel company.

1. Perpendicular Plates

Plates of this type are referred to as PP-MS or PP-80 depending on the type of material used. The first series had one vertical plate 8"x6" welded to a horizontal plate 12"x6". The fillet joint was made on the centerline of the 12" side of the horizontal plates. Two specimens were made for each material, mild steel and HY-80 steel. The second series of this group had two vertical plates 8"x6"

welded to a horizontal plate 18"x6". Fillet welds were made at 3 inches from both ends of the long dimension of the horizontal plate. Figures 2-1 and 2-2 illustrates the geometric configuration and station designations for the four types of specimens used in this study.

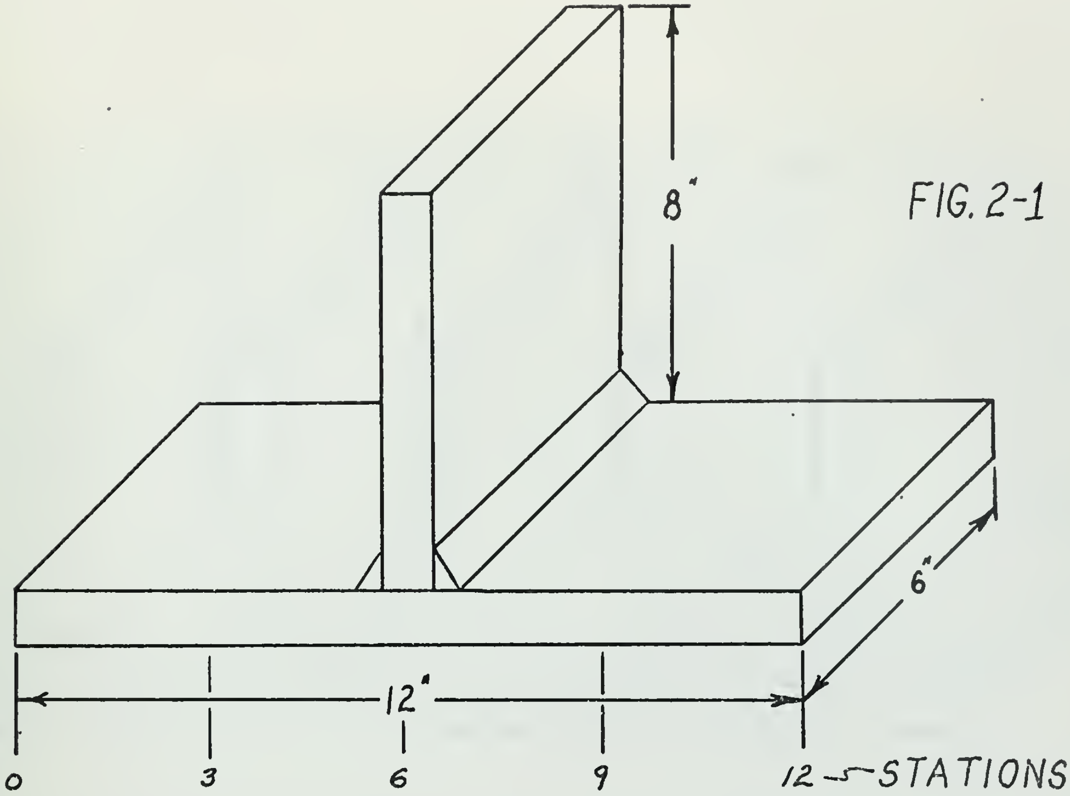
2. Free-end Structures

Specimens of this type are designated SF-MS. This structure had five vertical plates 8"x6" fillet welded at equal distances to two horizontal plates. The horizontal plates measured 3' and 2' long and were butt welded to give a total span of 5 feet. Two pass welds were made at the butt joint on the upper portion of the joint only. Butt welds were v-bevelled with a root face of approximately one-fourth inch, reference figure 2-5. Butt welds on all specimens were not evenly spaced between vertical plates. Instead they are offset approximately one-third the span between the two vertical plates. This procedure duplicates an actual method observed by the author at a local commercial shipbuilding yard. The shipbuilder commented that this procedure in ship fabrication reduces problems in match-up of prefabricated sections during final assembly operations.

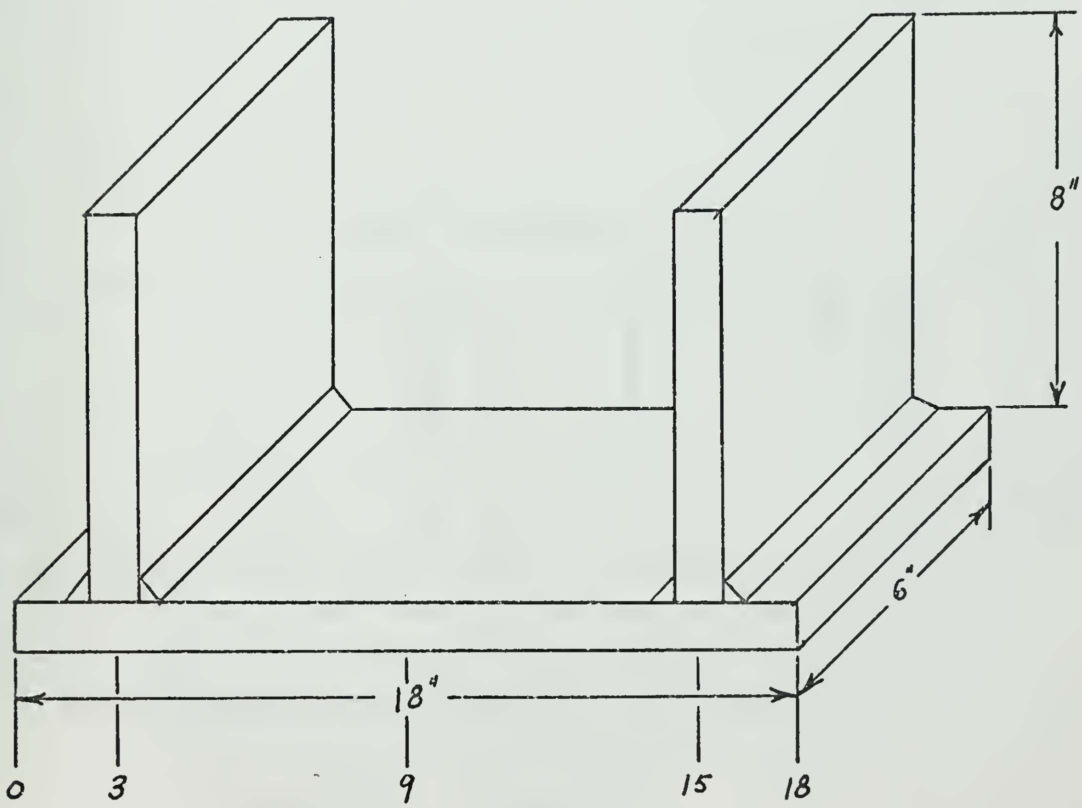
3. Rigid-end Structures

These specimens are designated SR-MS and SR-80. They are similar to the free-end specimens with the

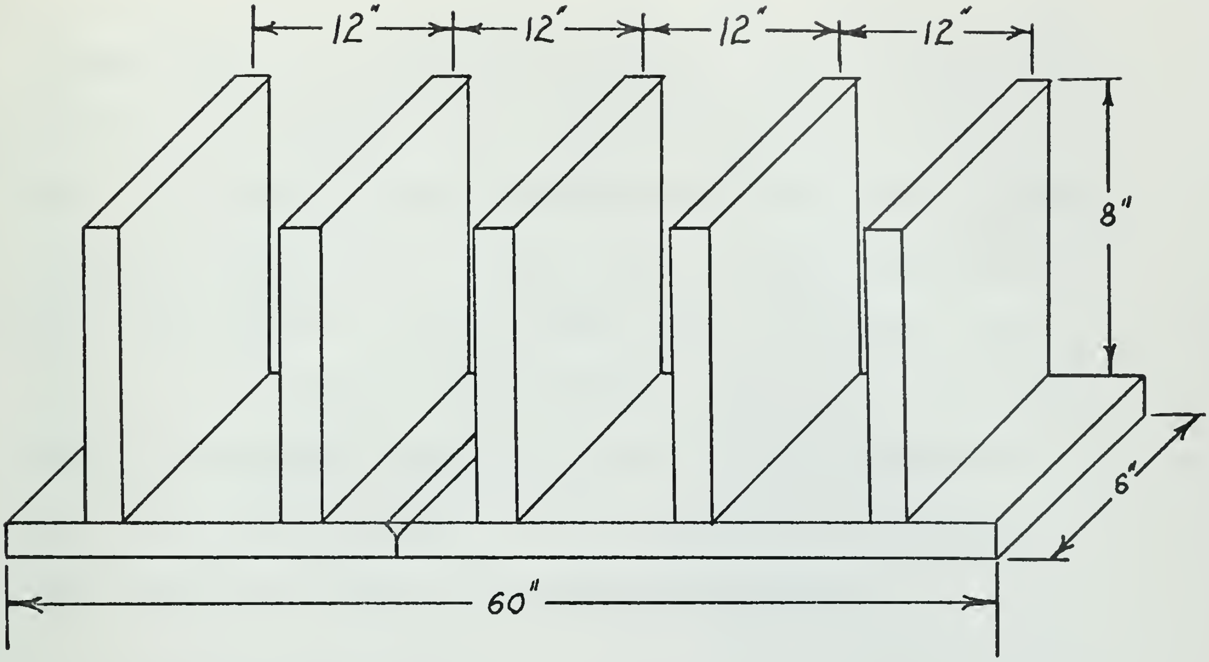
FIG. 2-1



PP-MS-1,2 ; PP-80-1,2

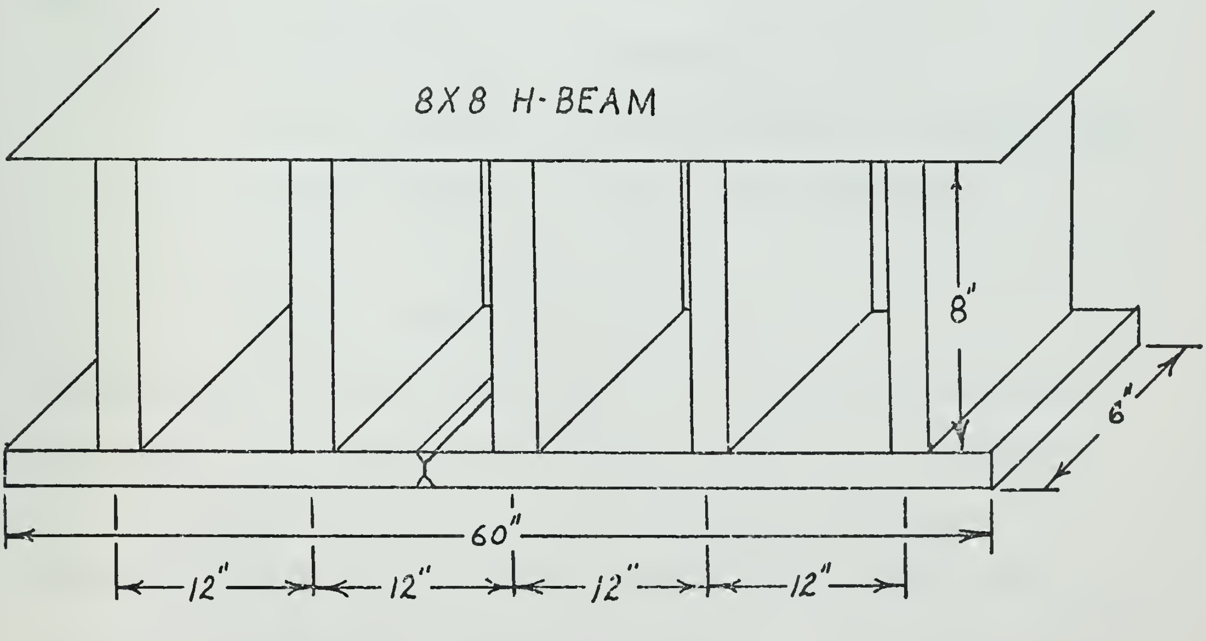


PP-MS-3,4 ; PP-80-3,4



SF-MS-1,2

FIG. 2-2



SR-MS-1,2 ; SR-80-1,2

exception the five vertical plates were welded to one flange face of the standard H-beam. First, these five plates were joined to the H-beam at equal distances of 12". Then the 2' and 3' horizontal plates were tacked welded into position for the final welding operation. Butt welds between the two long plates were two pass welds on both sides of the joint. The butt joint was double V-bevelled with a root face of approximately one-eighth inch. Fig. 2-3 is a photograph of this type specimen in the tack welded condition.

C. Welding Procedures

All welding with the exception of one perpendicular plate specimen was done by the author using a Westinghouse DC Welder, Type RA with the following characteristics:

Primary voltage: 550-440-220 volts

Primary current: 15-19-38 amp/ph at rated load

Welding current rating: 220 amperes

Cycles: 60, three phase

Voltage load: 40 volts

Double fillet welds were used to join all perpendicular test sections. The number of weld passes was desired to be constant at two for all specimens, however, to obtain adequate initial weld distortion for some test specimens additional passes were made. Table 2-1 indicates the number of weld passes made on each specimen.

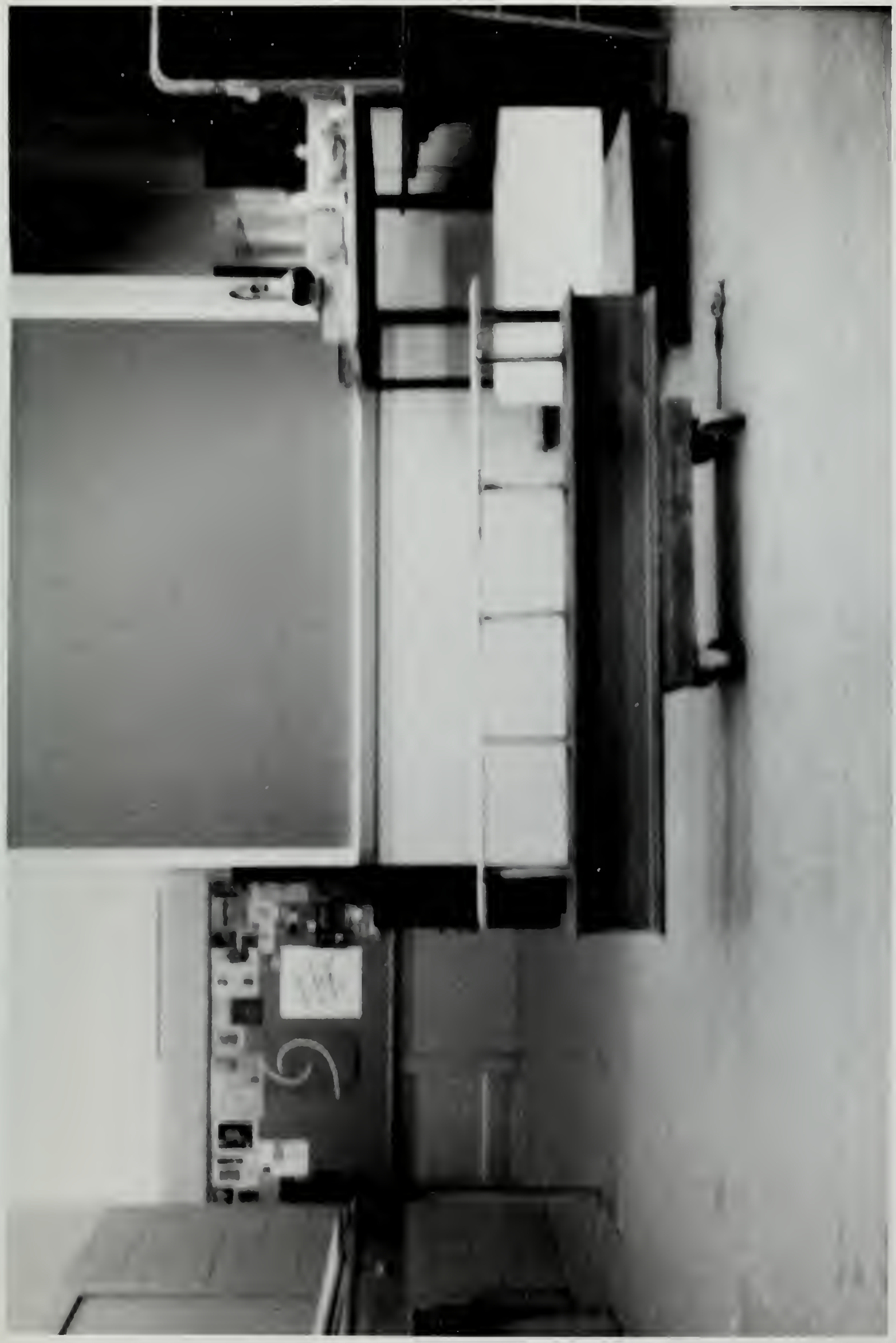


Fig. 2-3

TABLE 2-1

WELDING CHARACTERISTICS

FOR INVESTIGATIONS

	Specimen		
Characteristic	PP-MS	SF-MS SR-MS	PP-80 SR-80
1. Electrode:	E 7014	E 7018	E 9018
a. diameter	3/16"	1/8"	1/8"
b. tensile strength	72,000-82,000 psi	78,000 psi	94,400 psi
c. yield point	62,000-72,000 psi	69,000 psi	84,600 psi
d. elongation - 2"	23-32%	32%	27%
e. reduction of area	33-55%	70%	69%
f. specifications	--	MIL-E-22200/1	MIL-E-22200/1 MIL-9018
g. current range (for designated diameter)	180-280amps	90-150amps	90-150 amps
h. polarity	straight	reverse	reverse
i. type current	D.C.	D.C.	D.C.
2. I	190 amps	150 amps	150 amps
3. V	20 volts	20 volts	20 volts
4. Welding position	horizontal	horizontal	horizontal
5. n			
2	PP-MS-1,2,4	SR-MS-1 SF-MS-1,2	--
3	PP-MS-3	SR-MS-2	PP-80-1,2,3,4 SR-80-1,2
(weld passes)			

The sequence of welding has a considerable effect on the amount of distortion incurred by the material during the welding process. Optimum welding sequences are preferred, however, prefabricated structures later assembled at another point than fabrication often preclude optimum welding sequences. The welding sequence used for the preparation of structures for this study are not standard or optimum, however, the sequence was maintained constant for each series of specimens. Figure 2-4 illustrates the welding sequence used in preparing the different specimens.

Selection of covered electrodes used in welding free-end and rigid-end structures was based on actual use in ship construction. Electrodes E7018 and E9018 meet certain specifications for application in ship fabrication, and hence were considered appropriate for this study. Electrode E7014 used for the mild steel perpendicular plate specimens was selected as the initial choice for the preliminary experiment. Table 2-1 presents the welding characteristics used in the preparation of each specimen.

Actual welding of the perpendicular plates was performed at a welding stand. This made it possible to position the specimens to have the filler metal of the electrode bisect the perpendicular angle of the joint as the rod travelled the length of the weld.

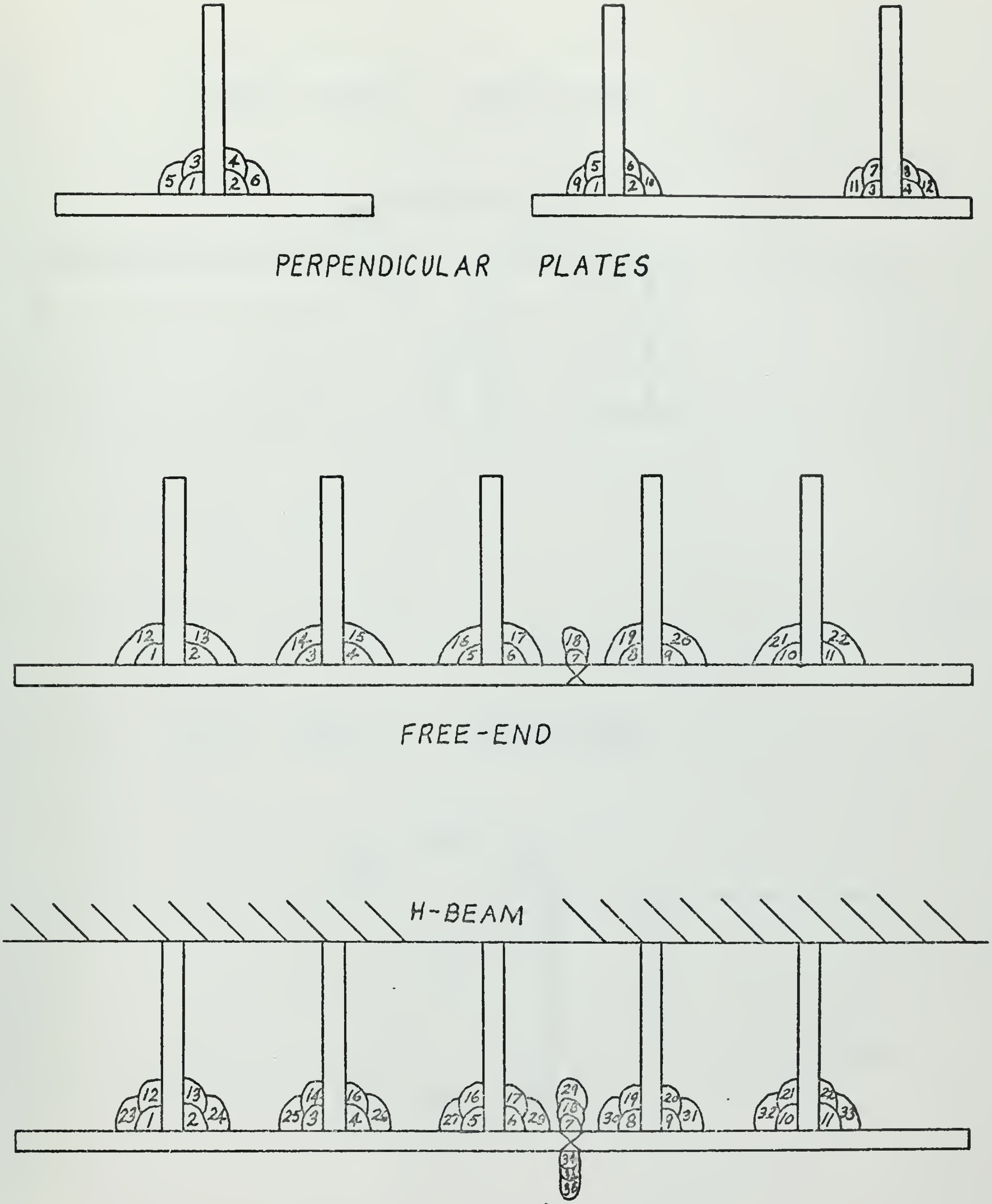
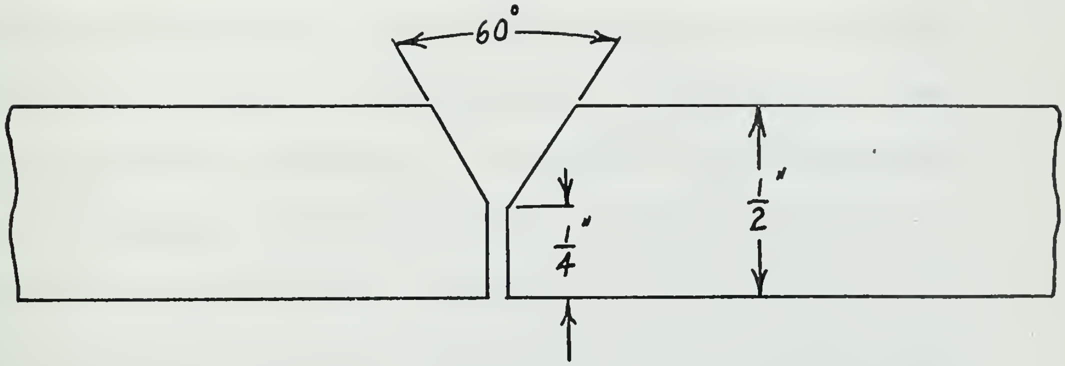


FIG. 2-4 WELDING SEQUENCE

BUTT JOINT FREE-END



BUTT JOINT RIGID-END

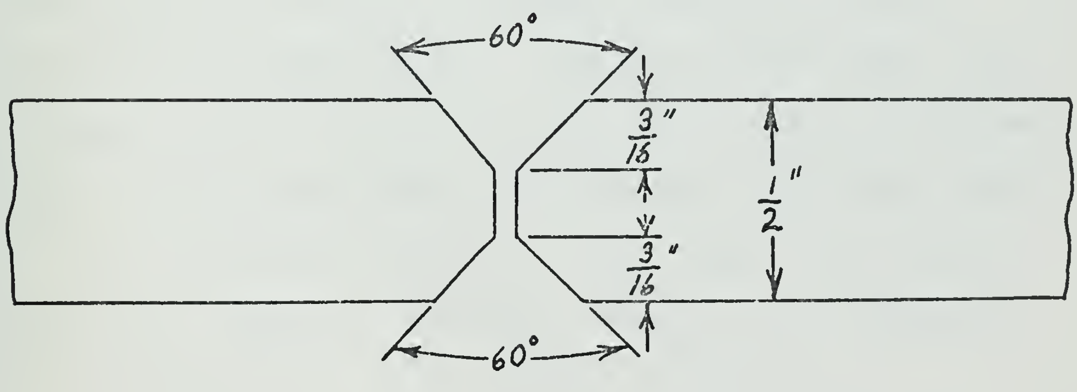


FIGURE 2-5

Free-end and rigid-end specimens were welded in place. The size and weight of the structures made this procedure necessary. Hence, the electrode passage for these specimens was made at an acute angle to the horizontal, whereas, the electrode passage for the perpendicular plates was made at a right angle from the horizontal position. All plates and structures were initially tack welded into position prior to commencing the welding operation. All welding was done in the horizontal position in lieu of vertical or overhead positions.

D. Experimental Procedures

During welding operations filler metal deposited in each weld was recorded. This was accomplished by taking an average of ten unused covered electrodes of each type to obtain an average weight of filler metal prior to consumption. After each weld pass, the remaining portion of the consumed electrode was weighed using a tri-balance scale. Percentage deductions were made for non-filler material in the flux. From these figures the amount of consumed material was obtained. Since distortion of fillet welded plates is a function of the amount of filler metal deposited in the fillet weld, a comparative analysis of the weld distortion in the specimens prior to flame heating and after flame heating is possible.

Flame heating procedures were performed with an oxy-acetylene rig using a number 30 size tip. For all flame heating tests on perpendicular plate and structure specimens, oxygen pressure was held constant at 20 psi and acetylene pressure was held constant at 4.5 psi. The flame heating torch tip was held at approximately 1 inch from the area to be heated at an angle necessary to have the flame perpendicular to the heated surface. Spot heating in lieu of line or panel heating techniques was used for all test runs. Water quenching sequence of the investigation was performed using a specially adapted hose and nozzle arrangement from a cold water faucet in the Materials Joining Laboratory. Water quench rate was held constant for all test runs at 3.36 in ^{3}/sec. Water temperature range was maintained constant at 70-75° F.

Maximum temperature ranges were indicated by Tempilstik Crayon Indicators furnished by Boston Naval Shipyard. Although thermocouples would have given a more accurate temperature indication, the indicator crayon was considered appropriate since it duplicates the actual procedure used in ship building. Also, since this investigation is concerned with distortion and its removal and not degradation in plate mechanical properties the crayon indicators are suitable as a maximum temperature indicator. In each test run when the desired area reached the appropriate temperature

it was immediately quenched using the water spray. The temperature reading was taken on the opposite side of the plate that was subjected to heating and quenching.

Plate and structure deformation measurements were taken after welding procedures were completed. Upon completion of flame straightening procedures measurements of deformation were again recorded. Designated stations for distortion measurements were every inch spacing for perpendicular plates and every two inches spacing for free-end and rigid-end structures. A reference plane was established after welding was completed. This reference plane and the specimen were fixed for all flame heating operations. Ames dial indicators, model 262, were used to measure distortion changes for the entire test sequence for each specimen. Heating position, maximum heating temperature, heating station and fillet weld station for each specimen is presented in Table 2-2. For heating position top refers to the side of the horizontal plate with the fillet joint, and bottom refers to the side without the fillet joint. Tables of data are presented in Appendix A.

TABLE 2-2

FLAME STRAIGHTENING PROCEDURES

Specimen	Fillet Weld Station (S)	Heating Station (S)	Heating Position	Maximum Temperature(T_H)
PP-MS-1 PP-80-2	6	6	bottom	1250 F.
PP-MS-2 PP-80-1	6	1, 11	bottom	1250 F.
PP-MS-3 PP-80-4	3, 15	9	top	1250 F.
PP-MS-4 PP-80-3	3, 15	3, 15	bottom	1250 F.
SR-MS-1 SR-80-1	8,20,32,44,56	14 26 38 50	top bottom top bottom	1200 F. 1200 F. 1480 F. 1480 F.
SR-MS-2 SR-80-2	6,18,30,42,54	6 18 30 42	bottom bottom bottom bottom	1200 F. 1250 F. 1480 F. 1500 F.
SF-MS-1	8,20,32,44,56	14 26 38 50	top bottom top bottom	1200 F. 1200 F. 1480 F. 1480 F.
SF-MS-2	8,20,32,44,56	8 20 32 44	bottom bottom bottom bottom	1200 F. 1250 F. 1480 F. 1500 F.

III RESULTS

The results of experiments on test specimens are in the form of distortion plots, tables and photographs. Appendix A contains a sample of the data.

A. Presentation of Data

The distortion plots show the amount of plate deformation along the chosen stations for the different test specimens. Figures 3-1 to 3-12 show graphical representations of post welding and post flame straightening deformation for specimens PP-MS-1,2,3,4; PP-80-1,2,3,4; SF-MS-1,2 and SR-MS-1,2. Tables 3-1 and 3-2 give the post welding and post flame straightening data for test specimens SR-80-1,2. Figures 3-13 and 3-14 give the post welded deformation for specimens SR-80-1 and SR-80-2.

Photographs presented in Figures 3-15 to 3-19 show some of the test specimens at various stages of testing. Figures 3-15 and 3-16 show specimens PP-MS-1 and PP-MS-3 in the post flame straightening condition. Specimens PP-MS-1,2, PP-80-1,2 and PP-MS-3,4, PP-80-3,4, respectively were similar in construction. Figure 3-17 shows specimen SF-MS-1 in the post flame straightened condition. Excessive deformation at either end of the structure is quite noticeable. Figure 2-3 shows specimen SR-MS-2 in the tack welded condition prior to welding and

flame straightening procedures. Figure 3-18 shows the same specimen in the post flame straightened condition. Figure 3-19 illustrates the effect of flame heating on the structure. Application of the flame was on the bottom of the structure at the center of the plate beneath the fillet weld. The scorched area around the weld is from the burning of the zinc chromate primer coat applied to reduce oxidation of the plate.

B. <u>Other Observations</u>

Deformations measured and indicated in this study are perpendicular to the plane of the plates, and are a measure of plate curvature between supports or from one fixed support to an unconfined edge. These results represent the deformation along the mid-span of the 6" side of all specimens. This was done to coincide with the flame heating application and quenching procedure at the center of the fillet welds or the center position of plates between supports. Deformation measurements, were read directly using dial indicators.

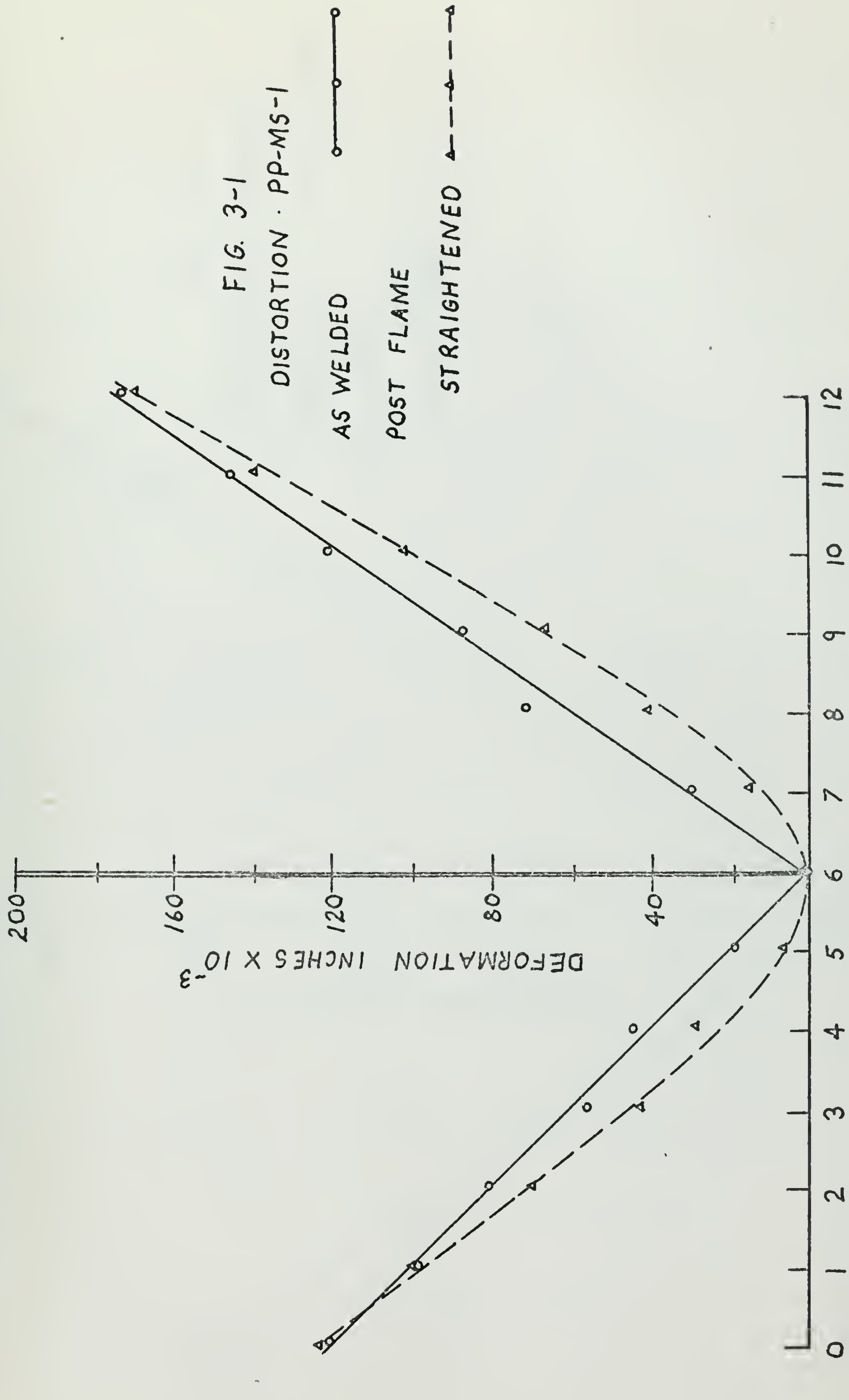


FIG. 3-1
DISTORTION · PP-MS-1

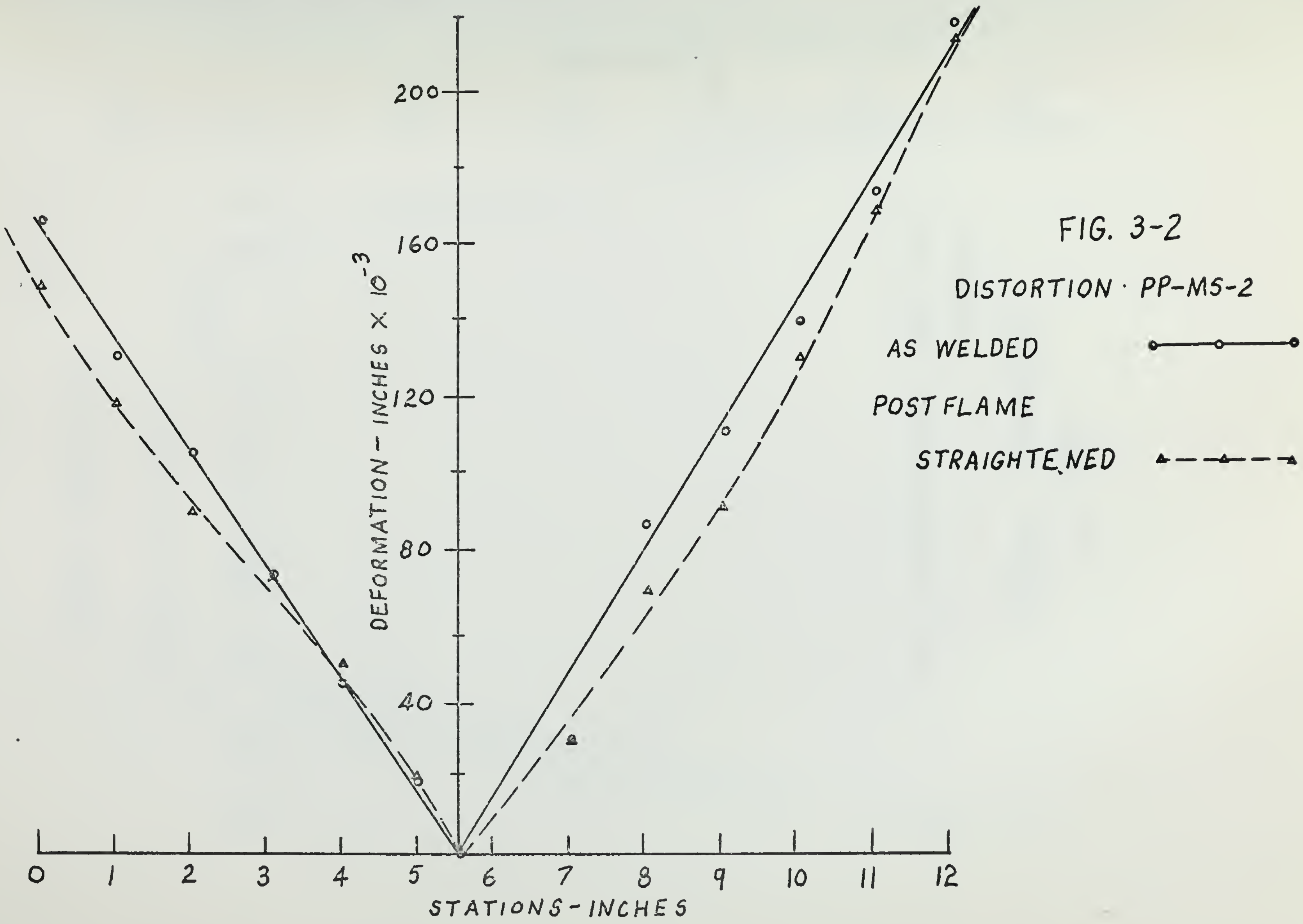

200
160
120
80
40
DEFORMATION - INCHES X 10^{-3}
0
1
2
3
4
5
6
7
8
9
10
11
12
STATIONS - INCHES
DISTORTION · PP-MS-2
AS WELDED
POST FLAME
STRAIGHTENED

FIG. 3-2

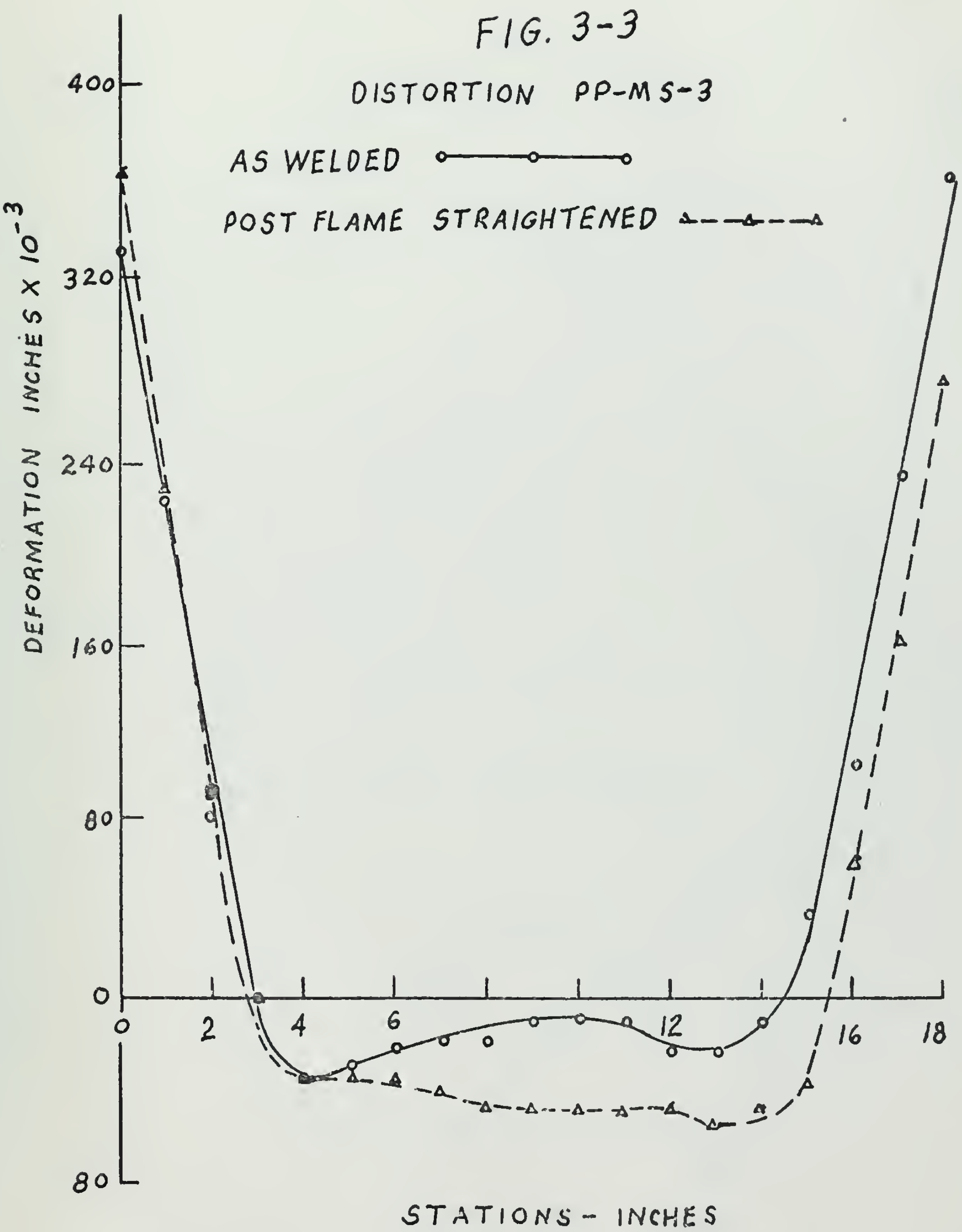


FIG. 3-3
DISTORTION PP-MS-3
AS WELDED
POST FLAME STRAIGHTENED
DEFORMATION INCHES X 10^-3
400
320
240
160
80
0
80
0
2
4
6
12
16
18
STATIONS - INCHES

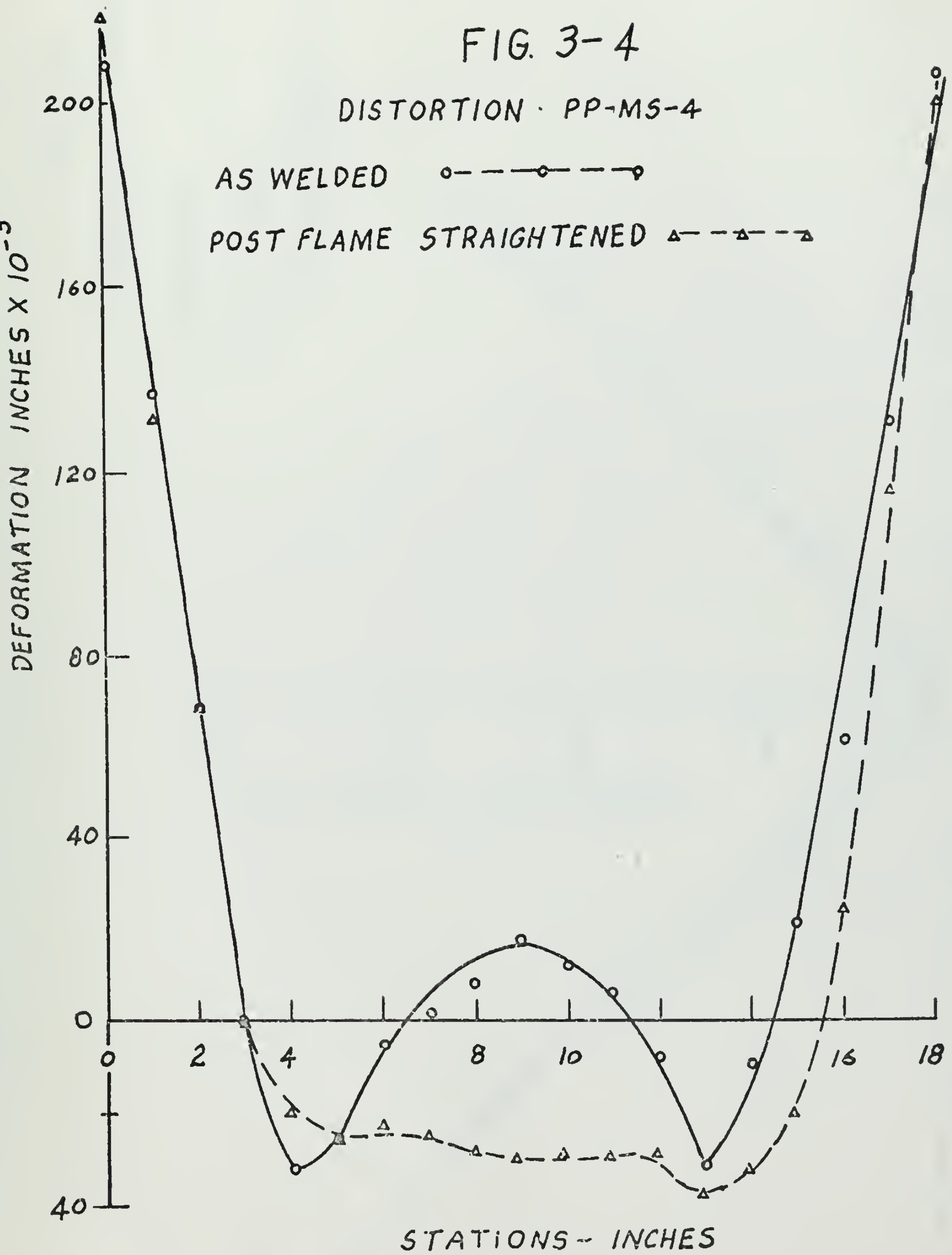
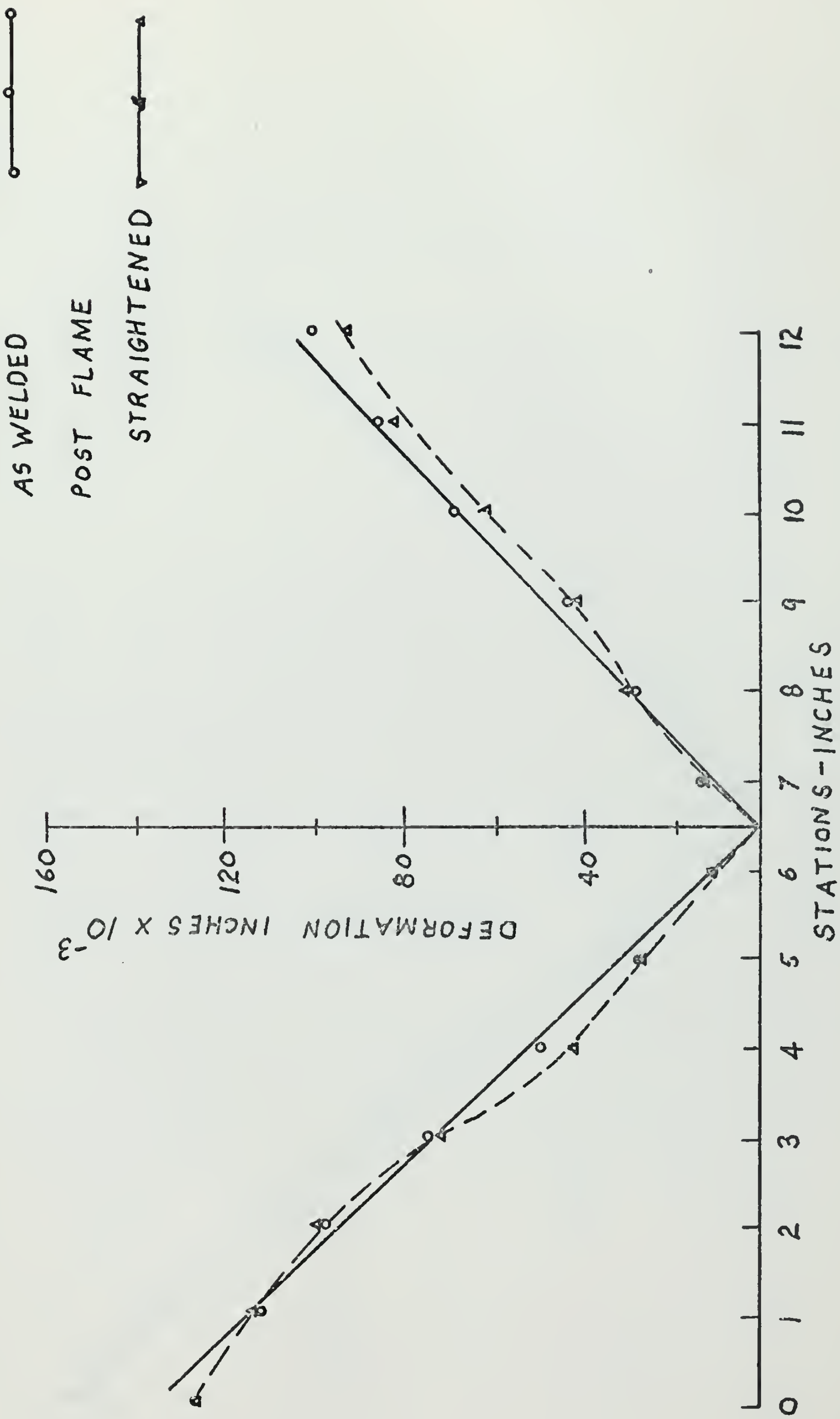


FIG. 3-4
DISTORTION · PP-MS-4
AS WELDED
POST FLAME STRAIGHTENED
DEFORMATION INCHES X 10^-3
200
160
120
80
40
0
40
0
2
4
8
10
16
18
STATIONS - INCHES

FIG. 3-5

DISTORTION PP-80-1



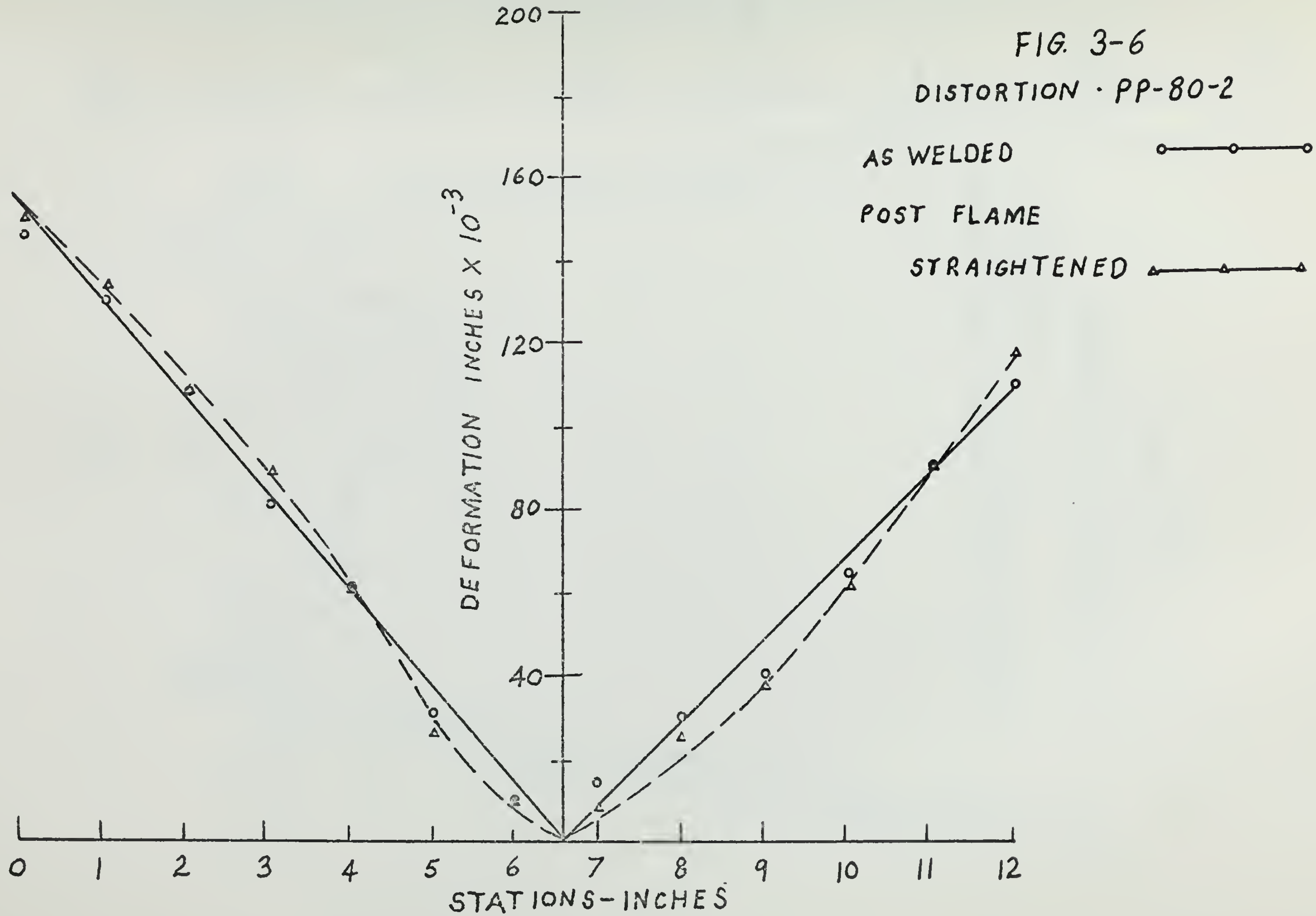


FIG. 3-6
DISTORTION · PP-80-2

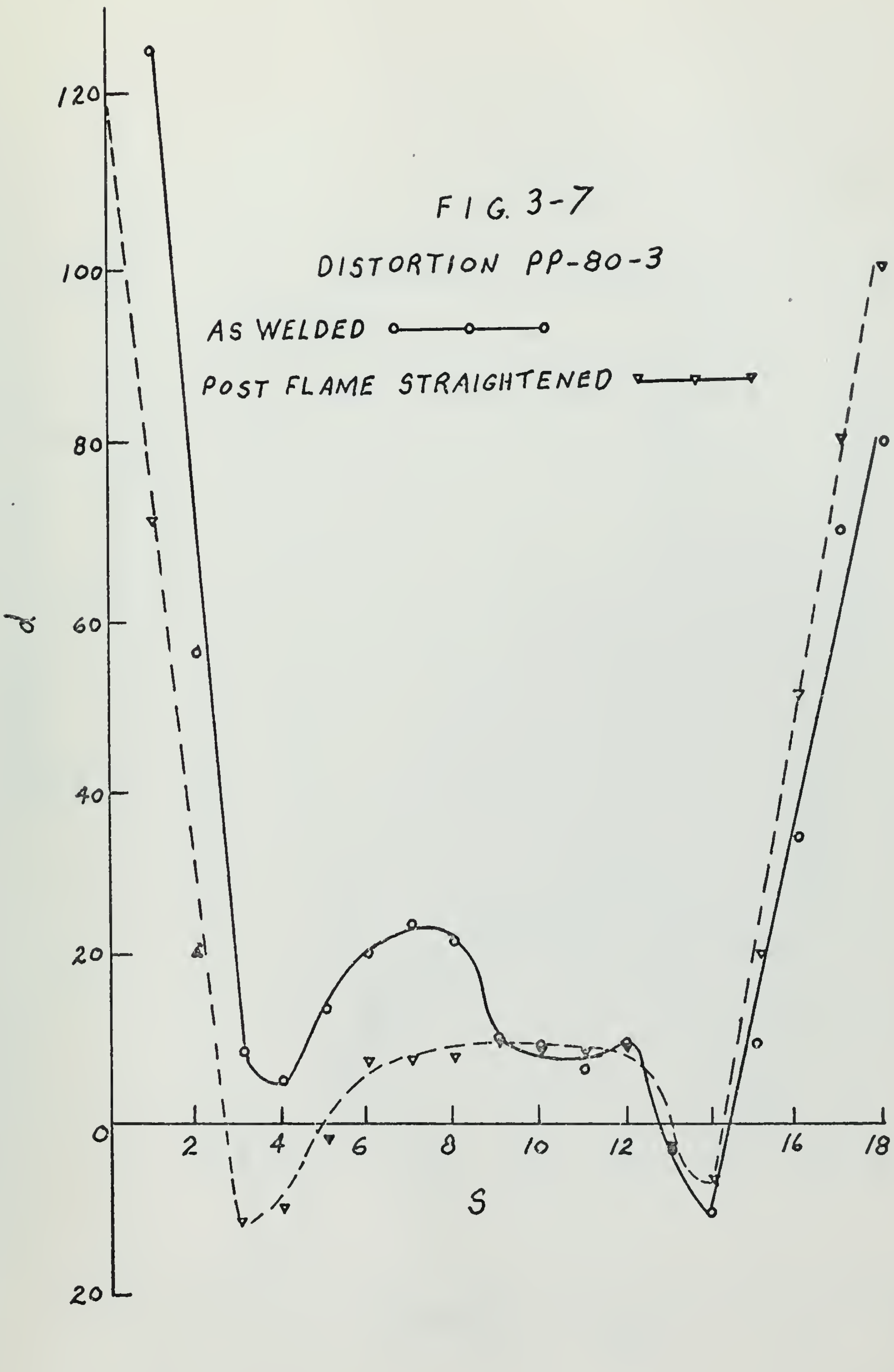


FIG. 3-7
DISTORTION PP-80-3
AS WELDED
POST FLAME STRAIGHTENED
120
100
80
60
40
20
0
20
δ
2
4
6
8
10
12
16
18
S

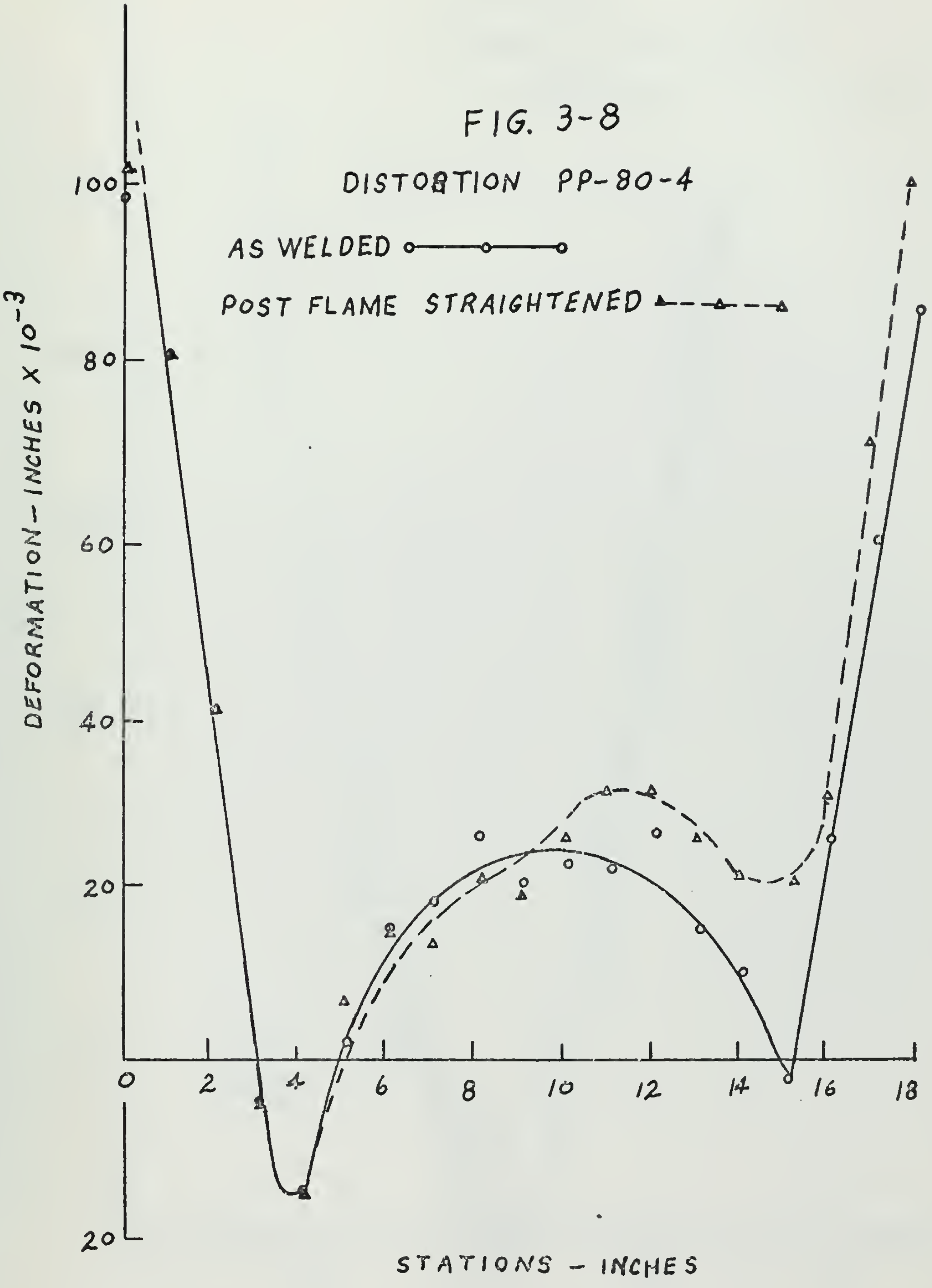


FIG. 3-8
DISTORTION PP-80-4
AS WELDED
POST FLAME STRAIGHTENED
DEFORMATION - INCHES X 10^-3
100
80
60
40
20
20
0
2
4
6
8
10
12
14
16
18
STATIONS - INCHES

FIG. 3-9

DISTORTION SF-MS-1

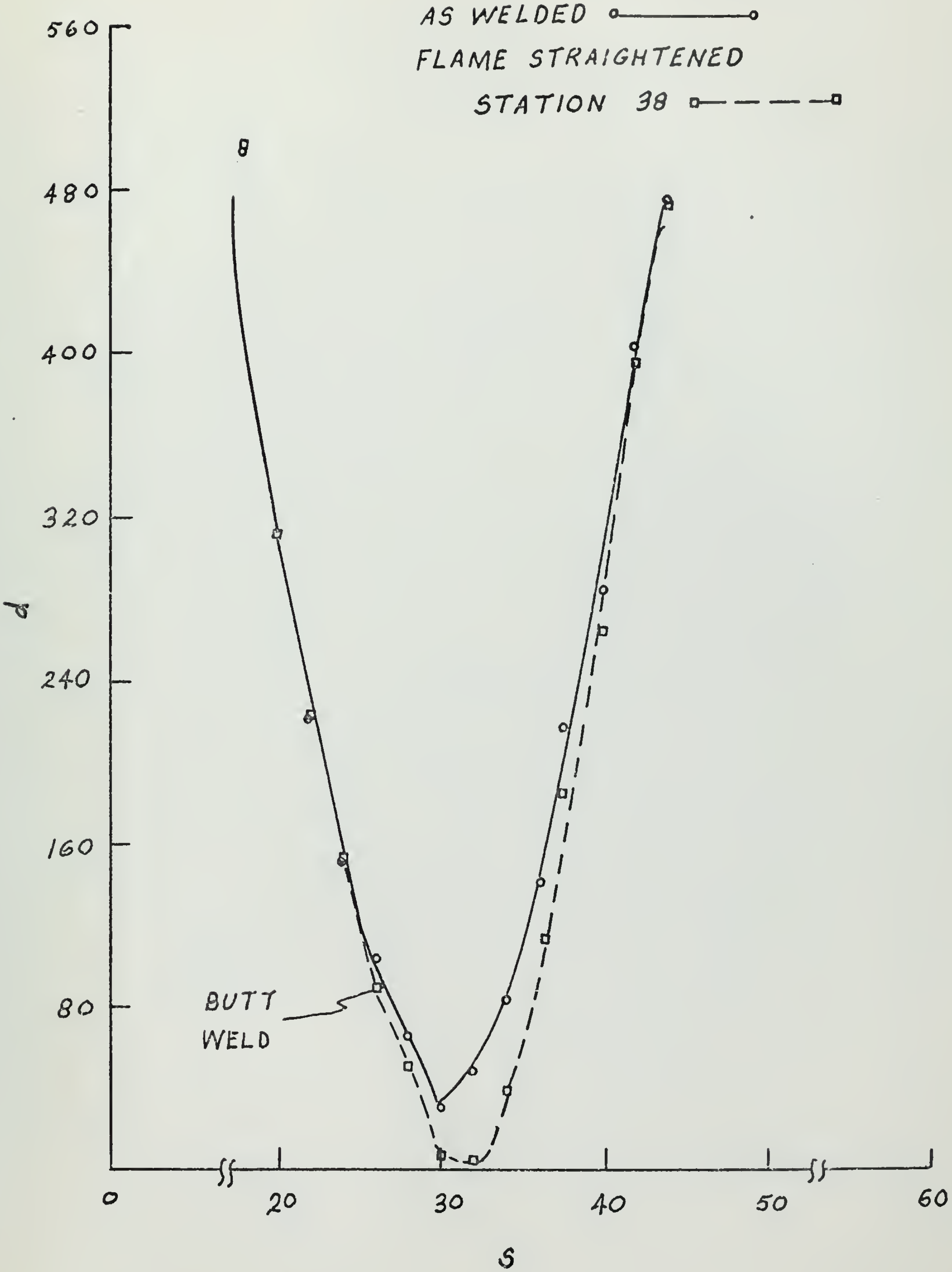
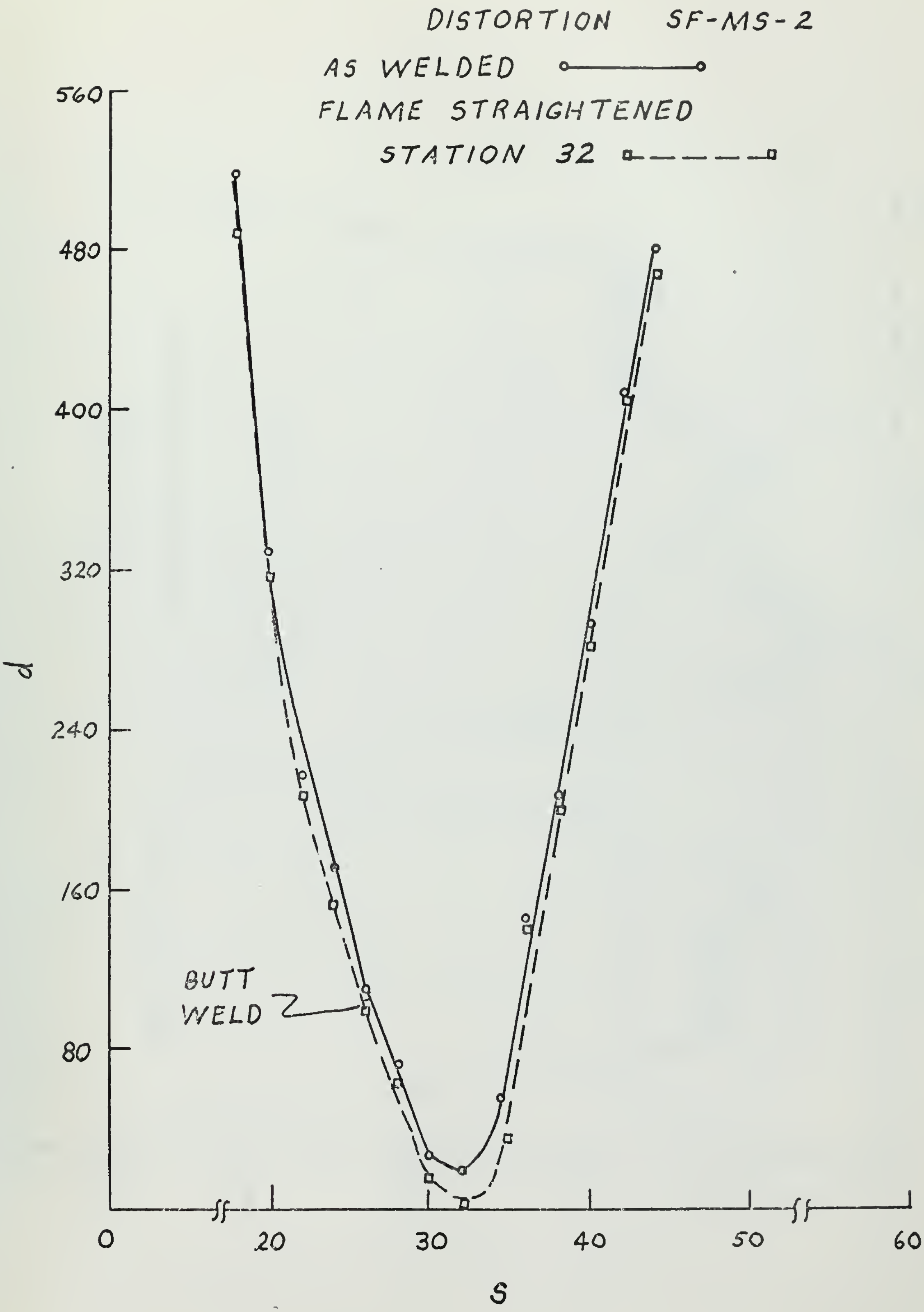


FIG. 3-10


DISTORTION SF-MS-2
AS WELDED
FLAME STRAIGHTENED
STATION 32
560
480
400
320
240
160
80
d
BUTT
WELD
0
20
30
40
50
60
S

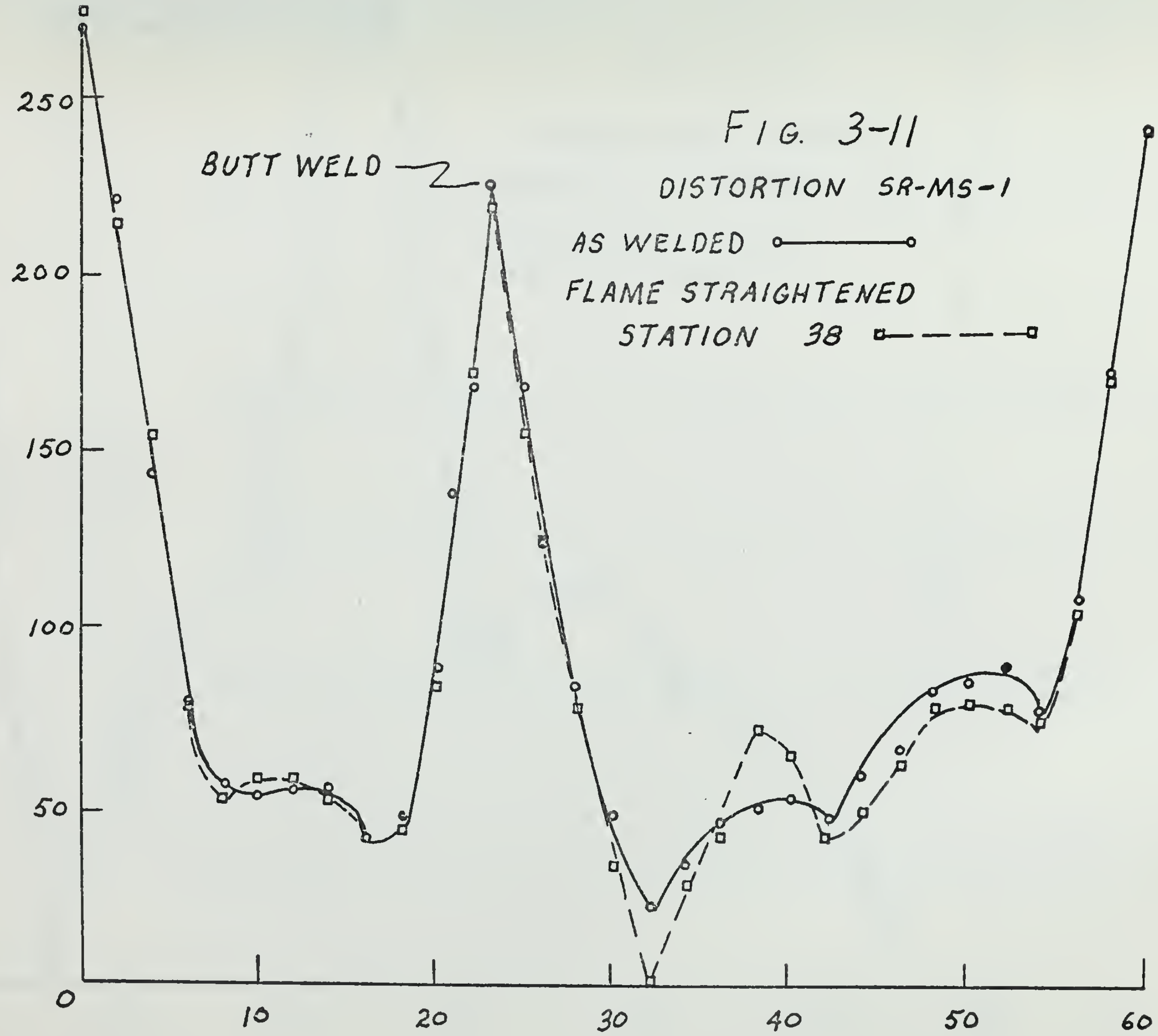

BUTT WELD
DISTORTION SR-MS-1
AS WELDED
FLAME STRAIGHTENED
STATION 38
250
200
150
100
50
0
10
20
30
40
50
60

FIG. 3-11

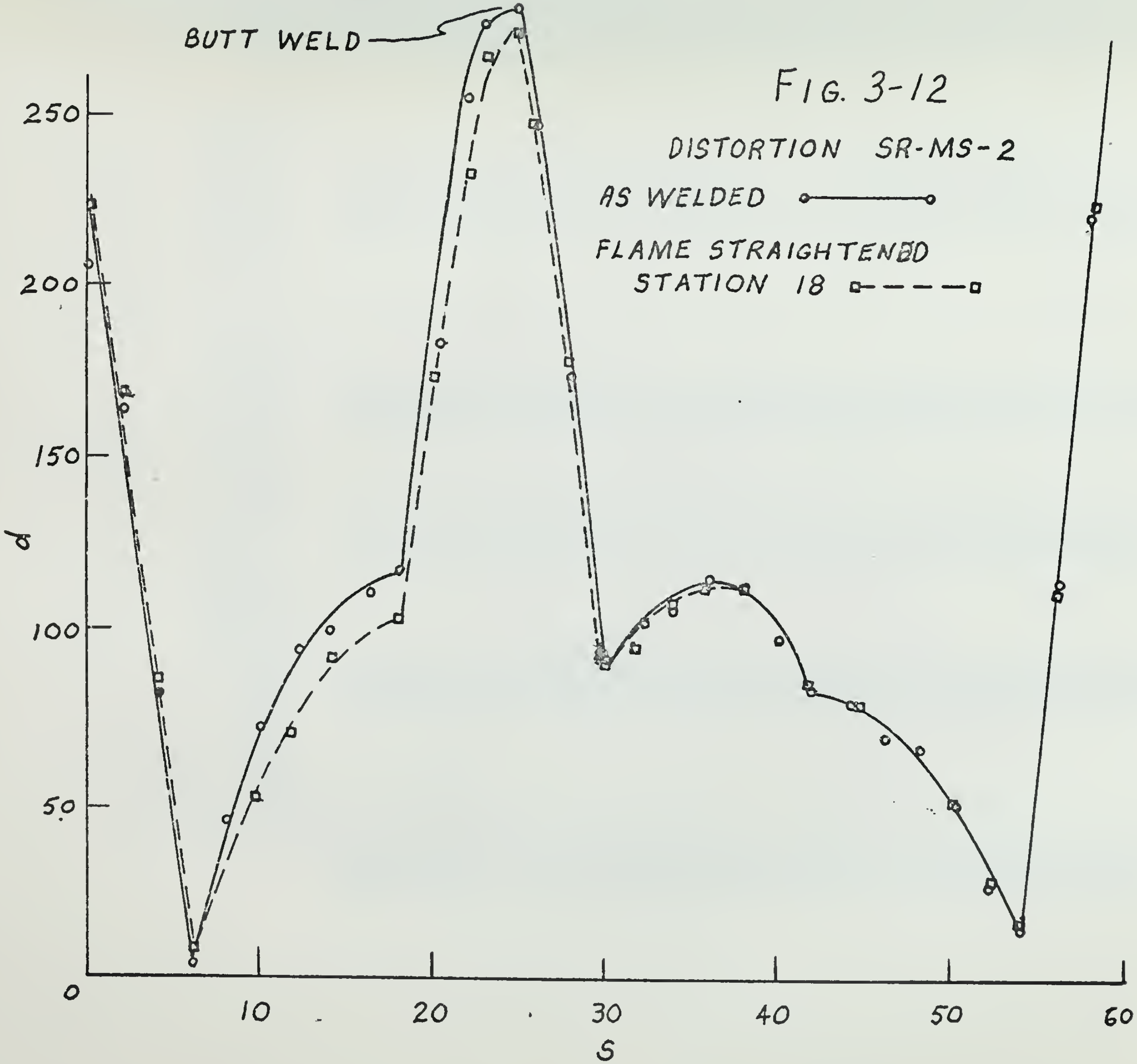

BUTT WELD
DISTORTION SR-MS-2
AS WELDED
FLAME STRAIGHTENED
STATION 18
250
200
150
100
50
0
10
20
30
40
50
60
S
d

FIG. 3-12

TABLE 3-1

DEFORMATIONS FOR SR-80-1

INCHES X 10^{-3}

Stations	Ref. Post-weld	Heating Sequences (Stations) 14	26	38	50
0	225	224	226	226	225
2	276	273	276	275	275
4	338	345	342	345	344
6	349	349	346	342	345
8	344	349	345	344	346
10	348	345	344	347	347
12	361	366	364	365	363
14	372	380	374	376	375
16	388	389	388	388	388
18	383	386	384	383	384
20	367	375	373	372	371
22	366	362	358	361	360
23	346	348	345	346	345
25	340	336	337	339	339
26	341	342	339	340	339
28	345	346	343	345	344
30	314	313	312	313	314
32	296	287	291	295	292
34	273	273	273	279	274
36	269	272	268	270	271
38	275	274	274	276	274
40	294	292	290	294	293
42	291	288	288	285	287
44	281	282	280	278	279
46	279	280	282	282	281
48	289	289	295	293	292
50	313	313	314	313	312
52	340	340	339	338	336
54	337	338	338	337	336
56	322	325	326	327	325
58	332	336	336	331	330

NOTE: Decrease in reading from reference value indicates a reduction in deformation, i.e. decrease in radius of curvature.

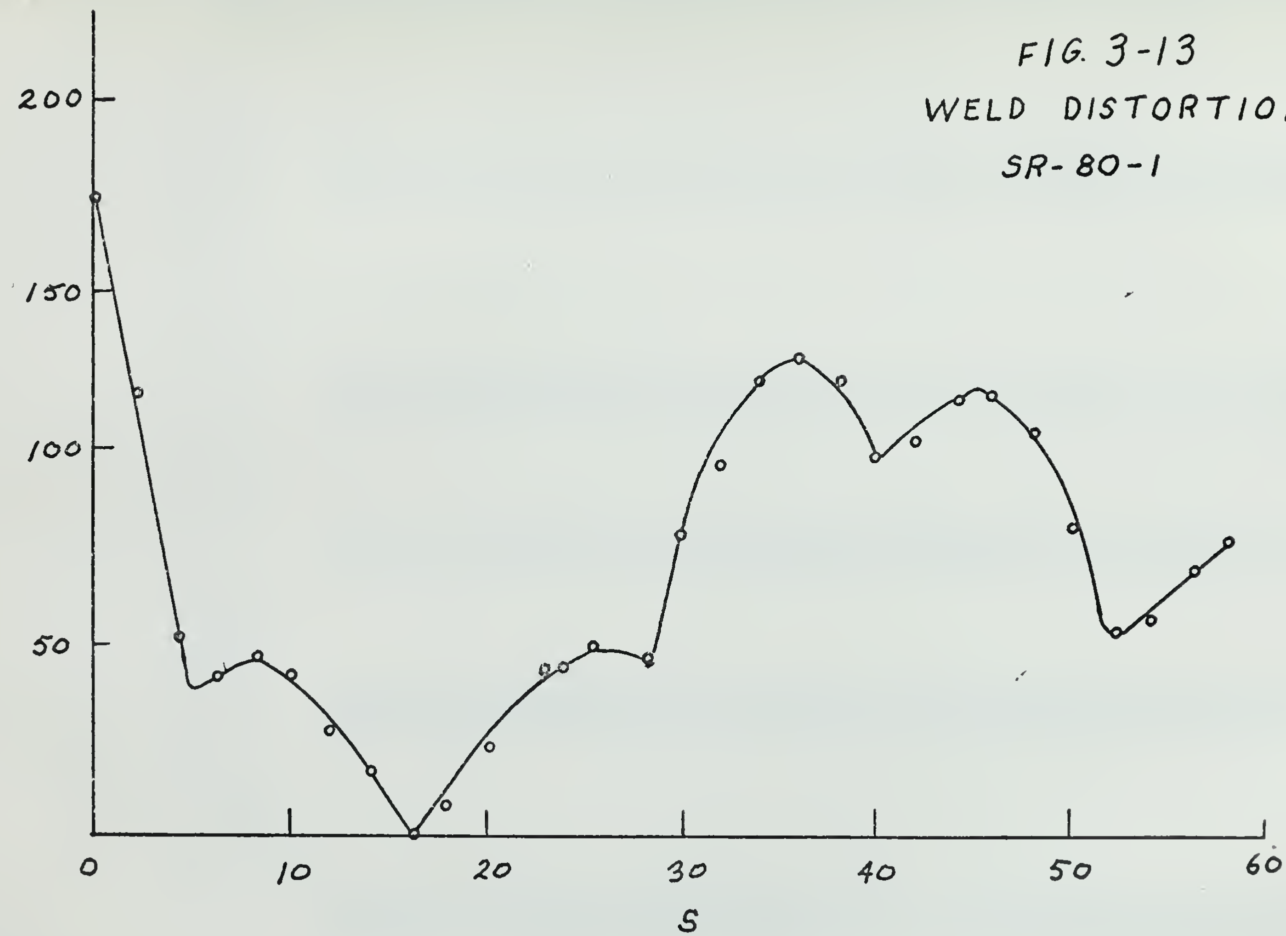


FIG. 3-13
WELD DISTORTION
SR-80-1

TABLE 3-2

DEFORMATIONS FOR SR-80-2

INCHES X 10^{-3}

Stations	Ref. Post-weld	Heating Sequences (Stations) 6	18	30	42
0	202	207	210	200	208
2	256	258	251	251	253
4	312	317	318	314	318
6	330	331	325	330	329
8	330	331	330	326	330
10	316	319	323	326	325
12	340	338	345	338	344
14	362	362	362	366	362
16	373	361	373	371	372
18	362	359	363	362	365
20	360	360	366	365	361
22	340	340	352	351	347
23	334	327	329	339	343
25	347	347	349	362	347
26	352	349	354	354	354
28	350	347	349	355	349
30	318	317	319	323	319
32	289	288	285	294	291
34	270	268	270	275	275
36	268	264	263	270	270
38	277	275	275	274	278
40	304	303	301	305	306
42	289	287	286	289	293
44	278	281	280	281	286
46	275	285	285	285	288
48	293	295	294	294	300
50	315	315	314	319	316
52	340	334	336	337	339
54	345	346	346	344	348
56	340	340	338	338	339
58	350	349	346	350	350

NOTE: Decrease in reading from reference value indicates a reduction in deformation, i.e. decrease in radius of curvature.

FIG. 3-14
WELD DISTORTION
SR-80-2

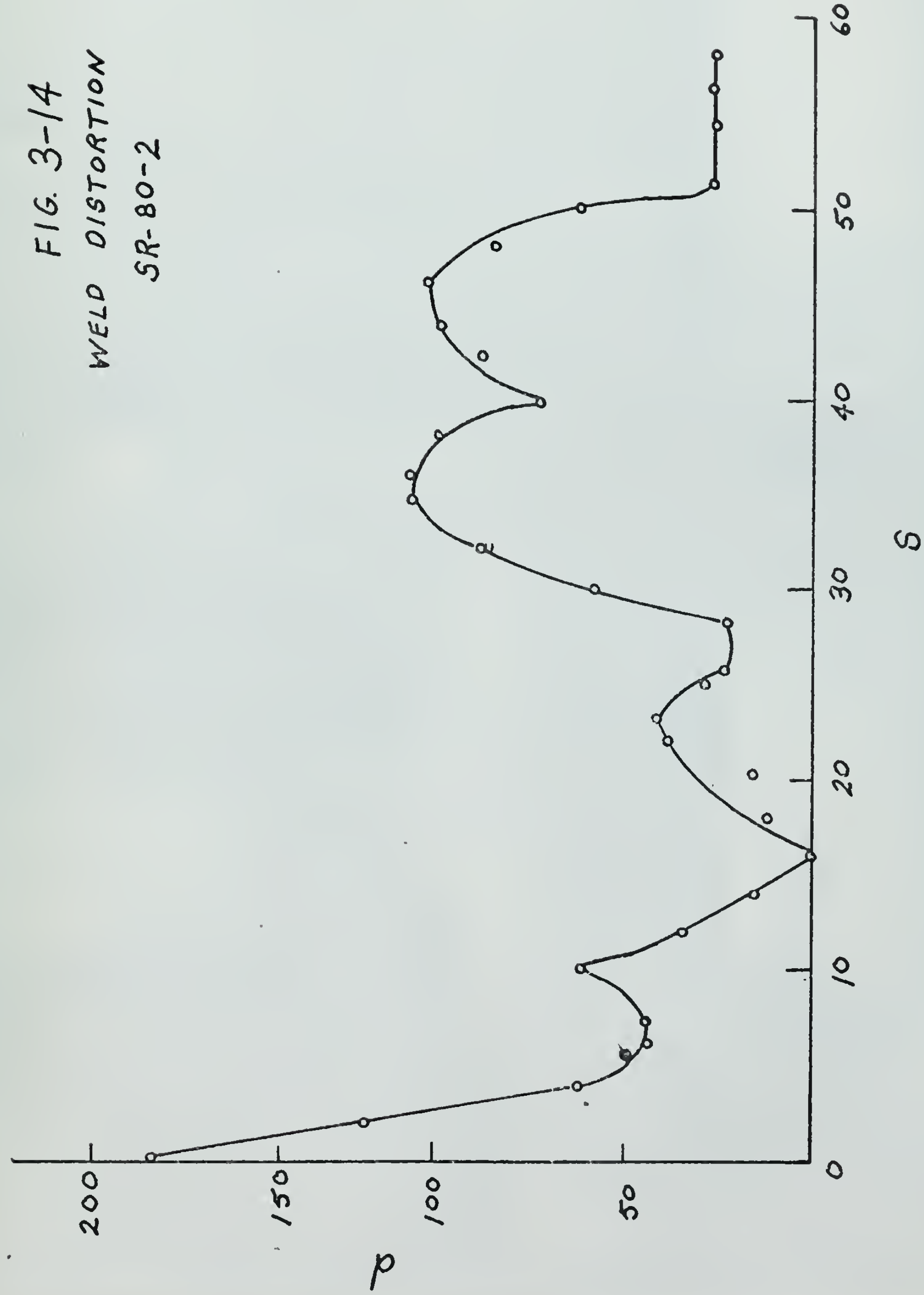


Fig. 3-15

Fig. 3-16

Fig. 3-17

Fig. 3-18

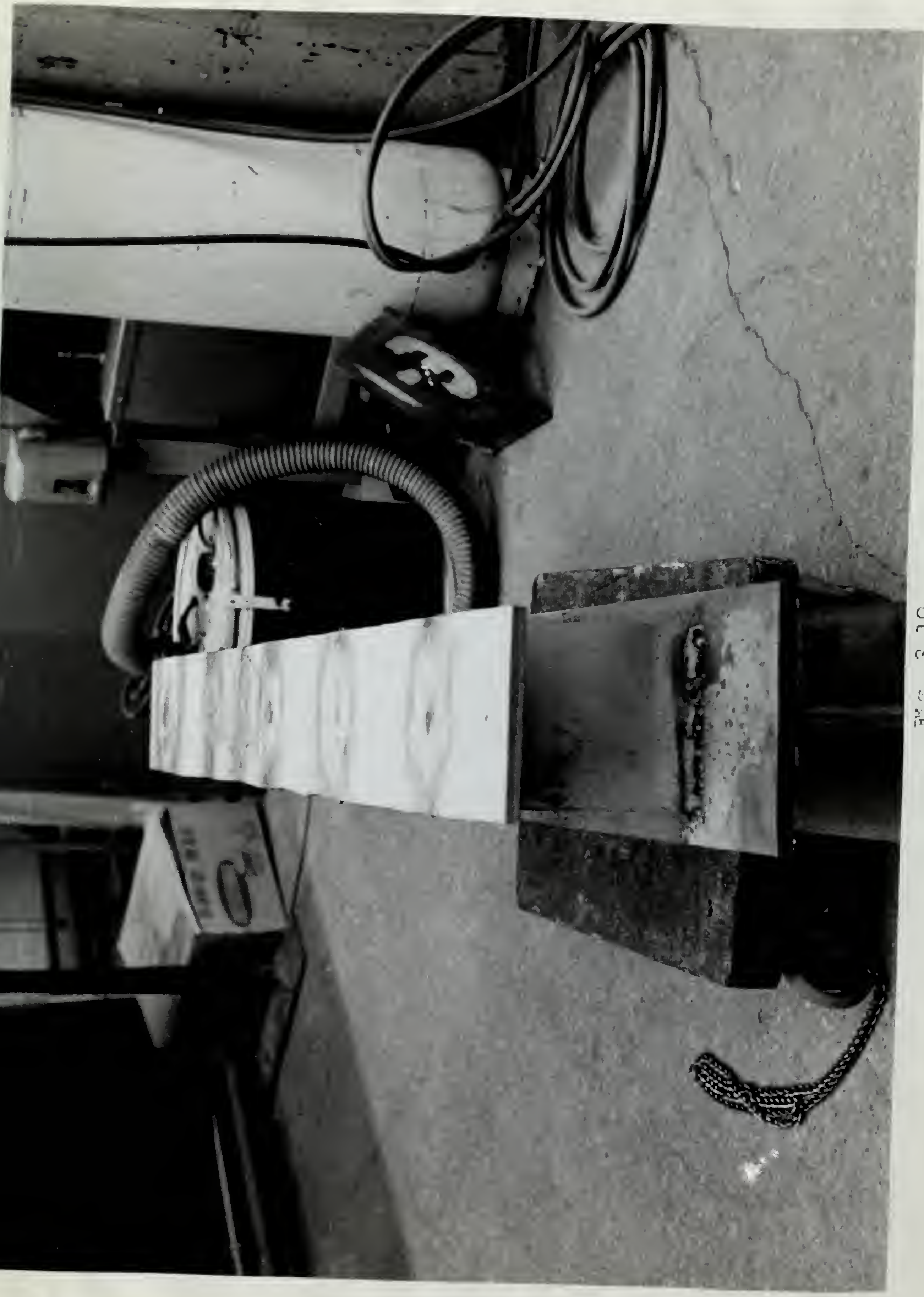


Fig. 3-19

IV. DISCUSSION OF RESULTS

A. Perpendicular Plates

The initial distortion resulting from the double fillet welded joint for unconstrained edges in these plate specimens is nearly a linear relationship; also the largest distortion results from an increased amount of filler metal deposited in the joint. All perpendicular specimens with unconstrained edges exhibit this phenomena(7). For plate spans between vertical members with equal deposits of filler metal in the welds, the deformation is practically symmetric in the form of a second order parabola. Specimens PP-MS-4 and PP-80-4* clearly show this result. For unequal deposits of filler metal in the fillet weld the plate span has a deformation which is asymmetric in the form of a third order parabola(5). Specimen PP-MS-3 more nearly approximates this condition.

After flame straightening operations, the steel plates in the immediate vicinity of the flame heated and water quenched area exhibit deformation changes which are not linear. This is caused by the metal being heated to a point where it enters a plastic region near the heated area while the cooler surrounding metal remains in

* Refer to figures 2-2, 2-3 and Table 2-2

an elastic region. Upon quenching from the plastic region the resulting change in deformation exhibits the non-linearity associated with plasticity whereas, the remaining deformation reductions in the specimen are nearly linear, characteristic of elastic behavior. All the mild steel plates with the lower yield strength show a greater and more uniform reduction in deformation from the as welded condition than the HY-80 specimens. For all the perpendicular plate type specimens, the mild steel plates averaged 2 1/2 times greater deformation reduction than the HY-80 steel counter-parts for the flame straightening techniques used.

An analysis of the effectiveness of the point of heat and water quench application on the amount of reduction in distortion yields no conclusive results for these type test samples. PP-MS-1 and 2 exhibit the same order of magnitude for deformation reduction even though flame straightening procedures differed. For PP-MS-4 where the flame was applied on the upper portion of the curved plate in the as welded condition, the distortion reduction was best achieved. As fig. 3-4 shows, the plate span between the two fillet welds (stations 3 and 15) is more uniformly straight as compared with the as welded condition. However, the initial

weld distortion of PP-MS-3 was asymetric, whereas, PP-MS-4 was nearly symetric. Therefore, comparing the former where the heat was applied beneath the fillet weld and the latter, produces no concrete results. A welding engineer at a local shipyard endorses the flame straightening procedures used on PP-MS-4 to produce less plate curvature between perpendicular supports or stiffeners. The justification being the upper portion of the curved plate is in tension and the bottom is in compression. When the upper portion of the plate is heated and quenched the resulting contraction force or "dilation"[11] in the upper edge acts in conjunction with compressive stress already existing in the lower edge to more effectively reduce the weld distortion throughout the whole plate span.

The irregular response of the HY-80 specimens preclude any justified conclusions relating reduction in deformation to the point of heat and water quench applications.

B. Free-end Structures

Test specimens of this type were restricted to mild steel material. Initial amount of HY-80 plates and problems in preparing adequate test samples precluded preparation of HY-80 specimens of this type. Mild steel specimens exhibit uniform and practically linear distortion in the as welded

condition similar to the unconstrained perpendicular plate specimens. Non-linear characteristics appear near the butt weld joint at about stations 26-30. Since there is no restraint on the structure weld distortion is transmitted throughout the entire structure in a linear relationship for the homogeneous plate. Successive fillet welding of additional vertical plates merely increase the overall distortion in the structure. Figures 3-9 and 3-10 show these results. This means the proper system model to study arc-form deformations must include a means for establishing a rigid boundary condition for vertical plates.

Flame heating techniques as outlined in Table 2-2 produced a similar response in these structures as in PP-MS-1 and PP-MS-2. Decrease in distortion were of the same magnitude for SF-MS-1 and SF-MS-2, although, flame straightening procedures varied. The important observation is the structure at the heated area reduced in deformation with progressively less reduction at distances remote from the heated area. Initially there was no "arc-form deformation"[5] between the vertical plates and no straightening between the vertical plates after flame straightening procedures were completed.

C. Rigid-end Structures

All test samples exhibit the arc-form deformation associated with this type structure[5]. Unequal deposit of filler metal in the fillet welds account for the irregular pattern in the post welded and post flame straightening condition. Automatic welding processes in lieu of manual, covered electrode welding procedures would produce more uniform filler metal deposits, therefore, more uniform deformation plots would be obtained. However, asymmetric and symmetric curvatures are represented in this type structure in Figures 3-10, 3-11, 3-13 and 3-14. Once again significant reductions in weld deformation after flame straightening procedures is noticeable for mild steel, while practically no change is discernible for the HY-80 test specimens as indicated by Tables 3-1 and 3-2. Varying the point of heat application does not produce any significant changes in the overall amount of deformation reduction for each method used. Flame straightening techniques using the higher temperatures, however, produce the greatest changes in deformation from the as welded condition. This means the highest temperature should be used consistent with the necessity of not changing the microconstituents of the material by heating to a high temperature and then quenching to room temperature.

D. Angular Distortion

Angular distortion varies for fillet welds in each type specimen. For PP-MS-1, 2 and PP-80-1,2 flame heating under the weld produces a decrease in fillet weld angular distortion. This results from plasticity effects in the immediate area of the flame. For plates that were flame straightened at the edges, the angular distortion is less reduced. In one instance, it slightly increased in PP-MS-2. Deformations were abrupt changes originating at the fillet welds for the above specimens.

For PP-MS-3, 4 and PP-80-3, 4 the angular change from one side of the fillet weld to the other has a continuous curve form associated with a protuberance below the plate axis for some test runs. For mild steel plates flame straightened at the mid-span considerable reduction in angular deformations were noted. For HY-80 material a very small change if any can be seen from Fig. 3-7 and 3-8. Flame straightening under the fillet welds for mild steel reduce angular deformations also. The change for PP-MS-3 was less than for PP-MS-4, however, in the former the initial weld distortion was less at the fillet joint also.

The free-end structure exhibited small changes in angular distortion for the structure as a whole. Changes resulted in the immediate

vicinity of the flame straightened area. The overall angular shape of the structure changed little from the as welded condition. Fig. 3-9 and 3-10 shows the area in the center of the structure. At each end the distortion is large (Ref. to fig. 3-17). There is noticeable difference in angular distortion characteristics for the free-end and rigid-end structure. The free-end specimens do not approximate shell plate and floor plate configurations.

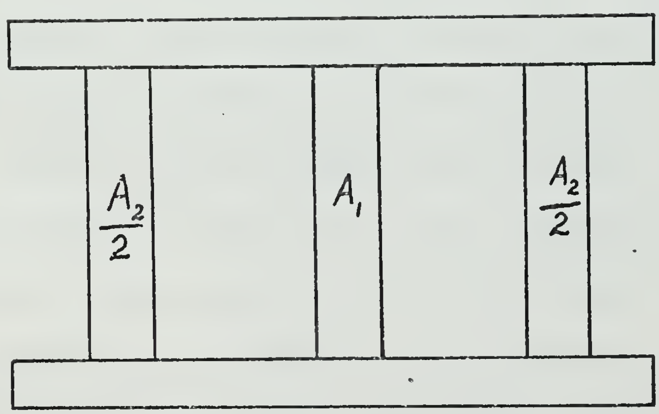
Rigid-end structures exhibit the desired arc-form deformation found in ship fabrication. Angular changes resulting from flame straightening procedures in general do not significantly change near the fillet welds. This implies the changes in plate curvature are found near the midspan of the plate sections. This is true even when there was lateral movement of the fillet weld being heated. On these structures the fillet welds at each end exhibit the same characteristics as the welds in PP-MS-3, 4 etc. This is to be expected since the boundary conditions are almost identical. Butt weld joints produce the greatest amount of distortion for this structure. Therefore, considerable attention must be given to reducing this distortion to acceptable limits. It is unlikely successive flame straightening would prove effective in accomplishing this reduction. The difference in the form of the butt weld distortion for SR-MS-1 and SR-MS-2 (figs. 3-11, 3-12) results

from the clearance between the two plates at the joint. Specimen SR-MS-1 had a narrower gap, hence, distortion was hindered by the reaction of both plates with one another during welding. This accounts for the sharp peak in fig. 3-11. For SR-MS-2 a larger gap was provided, thereby, producing a more uniform distortion transition from one plate to the other.

E. Mild Steel versus HY-80 Steel

In an attempt to explain the flame heating effect of mild steel and HY-80 a simplified system model was selected. This model consists of three bars. The middle bar represents the weld and heat-affected zone and the two outside bars represent the cooler base plates of the welded structure. This system model has proved useful for butt weld analysis and, it is assumed valid for a fillet weld condition.

Fillet Weld System Model



A_1 = heat-affected zone area

A_2 = surrounding metal area

In addition A_2 is assumed to be equal to twice A_1. With heat applied to the middle bar the stress in this bar as derived in Appendix B is:

$$\sigma = -\frac{\alpha E_2 \Delta T}{\left(\frac{E_2}{E_1} + \frac{1}{2}\right)} \tag{4.1}$$

This stress represents the thermal stress induced into the metal during flame heating. Young's modulus for the heated area changes with temperature, whereas, the modulus for the surrounding plate area is assumed to be constant. Also, the linear coefficient of expansion is assumed constant for the temperature range used in flame heating. Figure 4-1 graphically shows this stress for mild steel (line OM) and HY-80 steel (line OH) plotted on a yield stress versus temperature curve for the two materials. This figure shows that HY-80 has a larger upsetting stress, σ_H' than mild steel, σ_M' when quenching from an elevated temperature. This implies that greater deformation reduction would be obtained from flame straightening HY-80 steels than mild steel. However, experimental results show the opposite case exists. Therefore, the simplified system model assumed for the analysis is insufficient for fillet weld conditions. Computer programs for calculating stress in butt welds have been developed. However, the study of stress induced from welding along an edge of a plate characteristic of a fillet weld is just commencing.

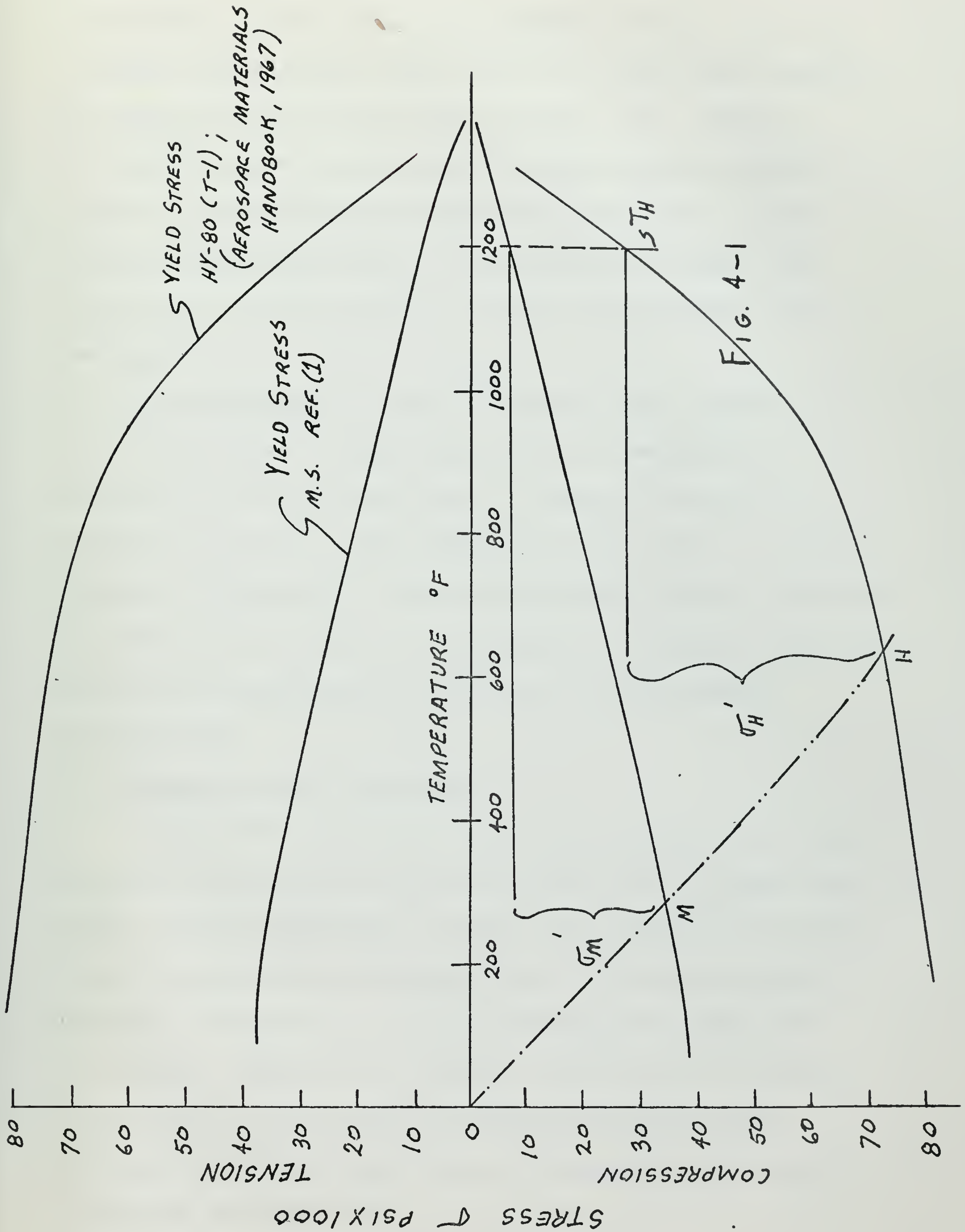

YIELD STRESS
HY-80 (T-1);
(AEROSPACE MATERIALS
HANDBOOK, 1967)
YIELD STRESS
M.S. REF.(1)
TEMPERATURE °F
200
400
600
800
1000
1200
σ_H
σ_H'
σ_M'
M
H
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
TENSION
COMPRESSION
STRESS σ PSI X 1000

FIG. 4-1

The result of this study will probably reveal that the thermal induced stress does not follow the relationships as shown by lines OM and OH in figure 4-1. Indeed, one would expect a more complex response of a fillet welded joint to thermal cycles associated with flame straightening techniques. This study may supply the explanation for the results found in this thesis investigation.

In extending Mr. Holt's[1] three basic facts concerning flame straightening from a homogeneous material to welded structures, a fourth item may be added to the list. This addition is the stress relationship as a function of temperature change for the structure or particular sections of a structure. Boundary conditions will have a considerable influence on this stress relationship.

F. Changes in Test Apparatus

Larger test specimens would allow greater accuracy in measuring angular changes resulting from welding and flame heating procedures. They would also make possible stress measurements associated with the two procedures possible. If this were done thermocouples should be used as the temperature indicator for greater accuracy. Measurement of the stress conditions would provide experimental data to plot the relationships for lines OM and OH in figure 4-1.

V. CONCLUSIONS

The conclusions of this investigation based on the preceeding discussion are:

A. Experimental observations;

1. Flame straightening procedures are 2-3 times more effective on mild steel than HY-80 steel.

2. Varying the position of flame straightening techniques from plate mid-span to fillet weld area produces no significant differences in reducing distortion.

3. There is no significant change in angular distortion at the fillet welds in rigid-end structure as a result of flame straightening procedures.

B. Observations from analysis of results;

1. The simplest experimental model specimen of shell plate and stiffener construction must have provisions for rigid boundary conditions for vertical supports.

2. For flame straightening procedures on welded structures reduction in distortion results from an upsetting stress and not yield stress alone. This upsetting stress (ref. to fig. 4-1) is influenced by the type material, flame heating temperature and stress condition in the welded structure.

3. A simple three bar mathematical model is inadequate to explain upsetting stresses in fillet welds subjected to flame straightening procedure.

VI. RECOMMENDATIONS

It is recommended that studies in this area be continued for different type materials with yield strength below that of HY-80. Results from these studies would provide a listing of materials within a corridor of yield strengths between mild steel and HY-80 where flame straightening would be effective. Expenditures for further studies of flame straightening procedures in HY-80 or higher yield strength materials seems unjustified because of the ineffectiveness of the procedure on these type materials. Aluminum and HTS steel are two suggested materials for future investigations. System models will depend on laboratory facilities, however, larger test sections are recommended to more closely approximate actual conditions encountered in ship fabrication. Future research on flame straightening for appropriate materials should be directed toward the ultimate objective of investigating panel sections which are encountered between longitudinal and transverse frames or stiffeners on ships. In addition, line heating and panel heating in lieu of spot heating should be explored. A concerted effort should be made to investigate new methods of reducing weld deformation. One possibility might be explosive shape charges. This latter approach may offer a better solution than refinements on present flame

straightening techniques.

Finally, it is recommended that analytical solutions be developed for response of welded joints to flame straightening procedures. These expressions would involve establishing a simplified system model of the joint to incorporate temperature distribution effects during rapid or slow cooling procedures. Analytic solutions for different materials would serve as a foundation to determine if there does exist a corridor of different yield strengths where flame straightening would be effective. These solutions using plasticity theory would provide knowledge about experimental results already observed, and would provide a basis for predicting future results under different boundary conditions.

APPENDIX A

EXPERIMENTAL DATA

DEFORMATIONS - INCHES X 10^{-3}

Station	PP-MS-1 Ref. Post-Weld	PP-MS-1 Post Heating	PP-MS-2 Ref. Post-Weld	PP-MS-2 Post Heating	PP-MS-3 Ref. Post-Weld	PP-MS-3 Post Heating	PP-MS-4 Ref. Post-Weld	PP-MS-4 Post Heating
0	148	158	130	145	130	72	209	188
1	171	174	164	177	249	209	291	280
2	186	203	189	204	381	344	360	339
3	211	230	220	218	465	433	428	408
4	222	245	247	244	500	466	460	427
5	250	267	275	271	495	468	452	431
6	267	273	281	280	491	470	431	429
7	238	253	262	262	485	479	427	435
8	197	234	206	227	486	484	421	437
9	181	208	182	201	489	482	410	439
10	146	170	152	162	475	483	415	436
11	123	135	118	124	477	483	421	438
12	95	104	75	81	490	483	435	437
13	---	---	---	---	484	490	450	447
14	---	---	---	---	471	483	437	440
15	---	---	---	---	430	471	405	428
16	---	---	---	---	361	388	365	382
17	---	---	---	---	236	280	296	308
18	---	---	---	---	97	165	212	213

DEFORMATIONS - INCHES X 10^{-3}

	PP-80-1		PP-80-2		PP-80-3		PP-80-4	
Station	Ref. Post-Weld	Post Heating	Ref. Post-Weld	Post Heating	Ref. Post-Weld	Post Heating	Ref. Post-Weld	Post Heating
0	142	141	164	167	101	132	112	114
1	156	154	180	178	124	179	125	129
2	171	168	203	208	192	220	171	171
3	192	196	229	227	243	263	214	216
4	219	224	249	254	245	260	224	225
5	240	241	279	290	238	254	209	205
6	257	255	300	305	230	243	194	195
7	254	256	294	309	227	240	193	194
8	239	237	280	290	229	242	187	190
9	223	227	270	275	242	242	190	192
10	198	204	246	252	244	243	188	186
11	181	184	219	223	246	242	188	180
12	167	174	200	197	242	241	184	179
13	--	--	--	--	255	255	196	184
14	--	--	--	--	260	257	201	188
15	--	--	--	--	242	230	212	190
16	--	--	--	--	216	202	185	170
17	--	--	--	--	170	150	125	111

SR-MS-1

DEFORMATION - INCHES X 10^{-3}

Station	Ref.Post-Welding	Heating Point (Stations) 12	24	36	48
0	189	178	192	187	192
2	237	233	240	245	243
4	315	302	302	306	305
6	379	372	376	380	372
8	403	394	406	406	406
10	406	508	404	402	402
12	404	402	407	400	407
14	403	403	402	404	408
16	418	415	420	419	422
18	412	413	417	414	412
20	370	374	368	375	375
22	293	290	290	287	282
23	236	235	243	240	240
25	292	290	317	307	309
26	335	332	337	333	335
28	374	370	376	381	380
30	411	410	424	426	425
32	439	439	443	450	455
34	425	426	429	432	425
36	414	413	416	420	413
38	400	400	393	388	393
40	397	398	399	397	397
42	413	413	416	418	422
44	401	400	405	411	418
46	394	396	391	397	402
48	376	378	375	380	373
50	375	377	372	382	357
52	371	370	372	382	354
54	383	381	385	386	359
56	352	352	354	355	342
58	287	286	290	290	287
60	219	217	216	219	198

SR-MS-2

DEFORMATIONS - INCHES X 10^{-3}

Station	Ref. Post-Weld	Heating Point 6	Heating Point 18	Ref. for 30,42,54 Stations	Heating Point Stations 30	Heating Point Stations 42	Heating Point Stations 54
0	164	155	149	--	--	--	--
2	206	209	202	169	165	165	163
4	288	285	283	243	242	240	237
6	368	364	365	332	329	329	324
8	325	341	338	302	302	300	306
10	298	311	319	286	283	281	280
12	275	293	299	260	259	258	257
14	272	278	278	238	240	236	233
16	267	269	260	222	224	221	220
18	251	272	267	230	227	225	222
20	187	189	196	159	162	159	153
22	117	120	139	098	105	098	096
23	094	101	106	070	078	075	070
25	090	088	094	056	073	073	065
26	125	124	126	093	104	105	102
28	197	192	192	160	167	165	164
30	278	281	279	241	236	234	233
32	269	272	275	239	245	245	249
34	262	265	262	228	236	239	237
36	254	254	257	223	227	236	233
38	258	257	256	224	230	246	238
40	271	267	267	236	240	247	240
42	288	285	285	254	256	271	272
44	290	289	291	261	262	279	275
46	301	299	299	265	266	275	272
48	302	305	306	275	273	286	278
50	320	318	318	291	289	298	293
52	345	344	345	317	318	321	322
54	356	357	357	330	329	328	333
56	257	259	261	230	230	235	242
58	151	145	146	118	121	115	125
60	064	064	066	--	--	--	--

SF-MS-1

DEFORMATIONS - INCHES X 10^{-3}

Stations	Ref. Post-Weld	Heating Point 14	Ref. for 26,38,50 Stations	Heating Point (Stations) 26	38	50
18	108	108	035	034	037	035
20	248	248	224	224	219	222
22	350	350	333	333	335	334
24	399	398	380	379	372	378
26	408	409	426	427	442	440
28	430	430	464	465	481	479
30	452	451	501	500	522	522
32	468	469	482	480	524	527
34	407	407	448	445	490	493
36	305	306	392	392	424	422
38	208	209	315	320	339	339
40	107	106	246	247	263	258
42	--	--	128	129	137	138
44	--	--	060	060	066	067

SF-MS-2

DEFORMATIONS - INCHES X 10^{-3}

Station	Ref.Post-Welding	Heating Position (Stations) 8	20	32	44
18	035	060	068	067	067
20	222	232	232	236	236
22	334	337	341	343	342
24	378	387	394	407	400
26	440	442	445	449	450
28	479	480	480	490	490
30	522	521	527	537	534
32	527	525	520	548	555
34	493	492	502	513	515
36	422	417	419	427	426
38	339	337	339	347	352
40	258	256	258	266	270
42	138	141	142	143	146
44	067	061	059	064	083

SAMPLE DATA

TOTAL ELECTRODE FILLER METAL CONSUMED

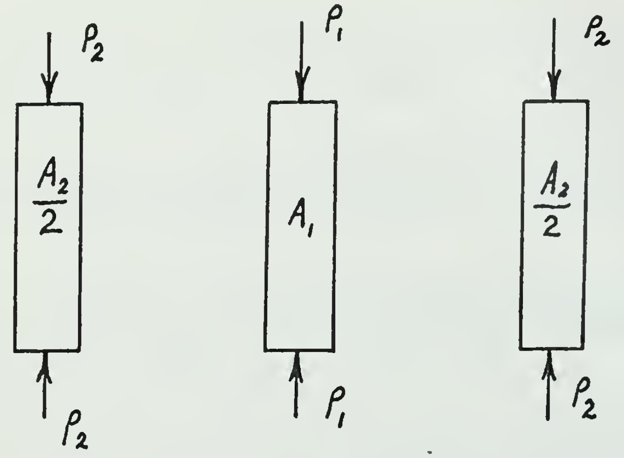
(in grams)

Fillet Weld Position

Specimen	1L	1R	2L	2R	3L	3R	4L	4R	5L	5R
PP-MS-1	75.00	72.00	--	--	--	--	--	--	--	--
PP-MS-2	69.25	60.50	--	--	--	--	--	--	--	--
PP-MS-3	74.50	62.90	68.15	71.80	--	--	--	--	--	--
PP-MS-4	69.25	62.80	61.50	73.85	--	--	--	--	--	--
PP-80-1	50.85	49.75	--	--	--	--	--	--	--	--
PP-80-2	46.50	46.40	--	--	--	--	--	--	--	--
PP-80-3	79.00	95.00	65.75	66.75	--	--	--	--	--	--
PP-80-4	44.21	47.40	43.23	45.80	--	--	--	--	--	--
SR-MS-1	40.60	34.00	38.60	35.90	42.20	39.92	39.30	35.55	38.38	35.65
SR-MS-2	60.99	46.72	56.83	54.65	59.50	52.45	63.00	58.50	62.63	51.50
SR-80-1	57.75	50.85	53.60	47.10	47.05	47.50	49.55	46.55	50.09	48.80
SF-MS-1	34.63	31.75	30.67	31.20	28.80	36.10	30.10	32.00	35.20	32.18

APPENDIX B

Calculations Fillet Weld Model - System Equations



$A_2 = 2A_1$

Force balance: $$\sigma_1 A_1 + \sigma_2 A_2 = 0 \quad (1)$$

Strain balance: $$\epsilon_1 + \epsilon_2 = \alpha \Delta T \quad (2)$$

Where: $$\epsilon_1 = -\frac{\sigma_1}{E_1} \qquad \epsilon_2 = \frac{\sigma_2}{E_2} \quad (3)$$

From (1): $$\sigma_2 = -\frac{\sigma_1 A_1}{A_2} = -\frac{\sigma_1}{2} \quad (4)$$

From (2), (3) and (4): $$\sigma_1 = -\frac{\alpha \Delta T E_2}{\left(\frac{E_2}{E_1} + \frac{1}{2}\right)} \quad (5)$$

REFERENCES

(1.) Richard E. Holt, "Flame Straightening Basics," Welding Engineer, Vol. 50 (1965) pp. 49-52.

(2.) Anonymous, "Flame Buckled this steel ... and Flame Straightened it!, Part I," Welding Engineer, Vol. 44 (1959) pp. 40-43.

(3.) Anonymous, "Oxy-acetylene Torches Straighten Fire-Warped Steel, Part II," Welding Engineer, Vol. 44 (1959 pp. 31-34.

(4.) F. H. Dill, "Flame Straightening, Forming and Cleaning Structual Steel," Welding Journal, Vol. 28 (1949) pp. 1066-1069.

(5.) Koichi Masubuchi, You Ogura, Yoshitada Ishihara and Jirou Hoshino, "Studies on the Mechanisms of the Origin and the Method of Reducing the Deformation of Shell Plating in Welded Ships," International Shipbuilding Progress, Vol. 3, No. 19, (1956) pp. 123-133.

(6.) LaMotte Grover, "Distortion and Shrinkage Problems in Ships and Other Large Structures, Part I," Welding Journal, Vol. 21, No. 10, pp. 665-675.

(7.) Hiroshi Kihara, Masaki Watanabe, Koichi Masubuchi and Kunihiko Satoh, Researches on Welding Stresses and Shrinkage Distortion In Japan, Society of Naval Architects of Japan, Tokyo, (1959).

(8.) T. Maeda and T. Yada, "Investigation on the Shrinkage Due to Multiple Spot Heating," International Institute of Welding, Commission X Document X-288-61 (1961).

(9.) B. S. Kasatkin and L. M. Lobanov, "The Thermal Stresses Caused in Plates by Spot Sources of Heat," Automatic Welding Vol. 18, No. 6, (1965) pp. 6-10.

(10.) Stanley I. Roberts, "A Thermal Expansion Study," Welding Journal, Vol. 45, No. 8, (1966) pp. 661-665.

(11.) T. Maeda and T. Yada, "Fundamental Nature of Shrinkage Distortion Due to Spot Heating on a Rectangular Plate," International Institute of Welding, Commission X Document X-327-63 (1963).

(12.) H. Kihara, M. Nisida and Y. Fujita, "On the Residual Stresses Due to Spot Heating," International Institute of Welding, Commission X Document X-267-61 (1961).

(13.) L. F. Bledsoe, "Repair of Welded Ships," Welding Journal, Vol. 27, No. 9, (1948) pp. 690-694.

(14.) B. Cotterell, "Stress Relief of Butt Welds in Rectangular Plates by Local Heating," British Welding Journal, Vol. 9, No. 5, (1962) pp. 326-329.

(15.) R. Malisius, "Practical Control of Shrinkage in Welding," Welding Research Council, Vol. XII, No. 7, (1957) pp. 10-22.

(16.) "Investigation on the Corrugation Failure of Bottom Plating of Ships," Report of the Shipbuilding Research Association of Japan, No. 19, (1957).

(17.) D. M. Kerr, "Welding Distortion in Shipbuilding," Symposium on Welding in Shipbuilding, Institute of Welding (1962) pp. 194-200.